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Final Report  
(July 1976 - August 1977)

DEVELOPMENT OF A PROTOTYPE  
REGENERATION CARBON DIOXIDE ABSORBER

By: Pinakin S. Patel and Bernard S. Baker

Distribution of this report is provided in the interest of  
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Prepared under Contract No: NAS2-9265

By

ENERGY RESEARCH CORPORATION  
3 Great Pasture Road  
Danbury, Connecticut 06810

For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
Ames Research Center  
Moffett Field, California 94035

October 15, 1977



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A B S T R A C T

A prototype regenerable carbon dioxide absorber was developed to maintain the environmental quality of the PLSS.

• The absorber works on the alkali metal carbonate-bicarbonate solid-gas reaction to remove carbon dioxide from the atmosphere of the EVA life support system.

The prototype sorber module was designed, fabricated, and tested at simulated EVA conditions to arrive at optimum design. The unit maintains sorber outlet concentration below 5 mm Hg, an important requirement of the PLSS. The smallest sub-unit of the module was life tested for 160 cycles of absorption-thermal regeneration-cooling with no appreciable drop in activity. An optimization study was made with respect to heat transfer, temperature control, sorbent utilization, sorber life and regenerability, and final size of the module. Important parameters influencing the capacity of the final absorber unit were identified and recommendations for improvement have been made.



## 1.0 INTRODUCTION

Future manned space exploration missions are expected to include requirements for astronaut life support equipment capable of repeated use and regeneration for many extra vehicular activity (EVA) sorties. The carbon dioxide removal subsystem is one of the most vital parts of the portable life support system (PLSS).

The purpose of this program was to develop a prototype, regenerable carbon dioxide absorber in order to gain a better understanding of both absorption and regeneration processes under dynamic flow conditions similar to those encountered in a real EVA mission.

Of the various subsystem concepts for repeated CO<sub>2</sub> removal from the recycled breathing gas of the EVA crewman, the potassium carbonate-bicarbonate has appeared to be the most promising<sup>(1,2)</sup>. The system utilizes the reaction chemistry of solid potassium carbonate forming solid potassium bicarbonate for removal and control of environmental carbon dioxide. Potassium carbonate, a safe, non-toxic chemical, reacts with carbon dioxide and water present in the ventilating gas to form potassium bicarbonate, which by the application of heat reverts back to the carbonate. The regeneration is completed at the low regeneration temperature of 150°C.

It was demonstrated (1) that carbon dioxide concentrations could be maintained below 0.76 mm Hg partial pressure by solid

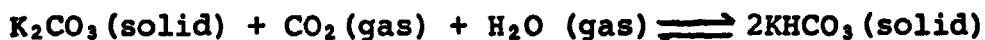
potassium carbonate dispersed and bound into thin (1 mm), pliable sheet material. The sheet sorbent form achieved sufficiently fast carbon dioxide reaction rates, ( $3.5 \times 10^{-4}$  g-CO<sub>2</sub>/g-K<sub>2</sub>CO<sub>3</sub>-sec. up to 75% conversion), good uptake capacity, and was capable of repeated use up to fifty cycles. An investigation was done of the most suitable method for packing the sorbent material into compact absorber units with proper gas accessibility to the sorbent (2).

To gain understanding of the carbon dioxide sorption and regeneration processes in mission-size units, a prototype absorber unit was designed, fabricated and tested under simulated EVA conditions. Effect of various design and operating parameters was investigated to arrive at optimum absorber design. Most influential parameters found are process temperature, L/D ratio and sorber unit configurations. The prototype sorber module was life tested for more than 160 cycles of repeated absorption and thermal regeneration. Further, two basic methods of regenerating the sorbent material after sorption of carbon dioxide were explored to identify possible system advantages of one method over the other. The two methods are thermal regeneration by heating to 150°C and regeneration by applied vacuum. A preliminary investigation of a combination of thermal regeneration with applied vacuum was made, which yielded very encouraging results.

## 2.0 BACKGROUND

Although the words sorbent and absorber are used to describe the carbon dioxide removal material and removal unit, respectively, the device is basically a chemical reactor with carbon dioxide bearing gas contacting a solid, consumable reactant, potassium carbonate. To achieve fast reaction rates and high utilization in the system with flowing gas streams containing rather low concentrations of carbon dioxide, the reactant is dispersed among a high surface area material and bound in place to form a thin porous sheet. The bicarbonate product formed is regenerated in place.

The basic reversible reaction taking place is as follows:



The high porosity and void volume of the sorbent material structure allow practical removal of carbon dioxide repeatedly. Exit carbon dioxide concentrations below 1.0 mm Hg partial pressure are achieved. Partial pressures near zero are thermodynamically possible at room temperature.

In manned system atmospheres, water vapor is present. Water is necessary for the above reaction and an excess of water over carbon dioxide is normally present and advantageous for carbon dioxide removal. This system, therefore, helps to remove water from the ventilating gases. Furthermore, potassium carbonate forms a hydrate  $\text{K}_2\text{CO}_3 \cdot 3/2\text{H}_2\text{O}$  as a side reaction in the system.

Water removed from the system with the carbon dioxide unit benefits the life support system humidity control device, reducing its load and size. The non-regenerable lithium hydroxide canisters used to remove carbon dioxide in previous life support systems added water to the system.

### 3.0 ABSORBER MODULE CONSTRUCTION AND TESTING

Absorber construction procedure and test facility were modified to meet the requirements imposed by the prototype module (6).

#### 3.1 Sorbent Material Preparation

The active sorbent material contains reagent grade potassium carbonate dispersed among high surface area silica gel and bound in place with a polytetrafluoroethylene (PTFE) binder. An optimum sorbent composition determined in previous feasibility study was employed to construct the sorbent sheet (Table 1). The optimum sorbent composition removes the maximum amount of carbon dioxide for the least total sorbent weight and remains most stable and active against repeated thermal regenerations.

TABLE 1

Optimum Sorbent Composition

| Component           | Composition<br>wt% |
|---------------------|--------------------|
| Potassium Carbonate | 43-44              |
| Silica Gel          | 53-54              |
| Teflon (PTFE)       | 3                  |

The preparation procedure followed was the same as that in previous study employing machine processing, blending followed by calendering (sheet producing) (4). The sorbent material could be prepared in various thicknesses, widths, and lengths. Typically, the sheet dimensions were  $1.14 \pm 0.076$  mm in thickness,

steel rule die cut to  $14.61 \pm 0.076$  cm in width, and cut into lengths of approximately 1.0 meter. S.E.M. (Scanning Electron Micrograph) picture and pore size distribution plots for some typical sorbent sheets having optimum composition are presented in Appendix A. The porosity of the sorbent sheet is in the range of 88-94% which makes it suitable for carbon dioxide absorption application.

### 3.2 Absorber Unit Construction

An axial flow cylindrical design was chosen for the absorber unit because of construction simplicity, simple flow distribution and radial symmetry. A cylindrical sorbent material core was constructed and inserted in a metal test canister. The sorbent core was made by spirally winding the long, thin sorbent sheets with a corrugated aluminum expanded-metal screen. The peak-to-peak corrugations of the aluminum separator screen formed the axial gas flow channels. The approximate channel space between sorbent sheets was 0.64mm, and the average sorbent thickness was 1.14mm. Aluminum is lightweight and a good conductor of heat.

After fabricating many cores, a stable physical arrangement was found. The aluminum separator material used was 0.203mm thick, 1145 aluminum base metal sheet, pierced and expanded to form a screen-like material with an open area of approximately 62%. The weight is about 0.021 grams per square centimeter.

### 3.3 Absorber Test Station

A test facility was constructed to obtain performance data of absorber units under varied conditions representing EVA specifications. A pictorial view of the CO<sub>2</sub> sorber module test station is given in Figure 1. As shown schematically in Figure 2, carbon dioxide gas was mixed with air to simulate suit vent gases. The concentration of carbon dioxide and water vapor in the air streams were continuously monitored by infrared analyzers.

The test station could provide atmospheric air streams to the absorber units with carbon dioxide concentrations from 1.0 to 40mm Hg partial pressure at flow rates up to 283 liters per minute STP.

A multipoint thermocouple scanner and printer was installed with the instrumentation. The direct readout in degrees facilitated temperature monitoring. The present test facility is a modified version of previous work (4). The modifications were necessitated by requirement of active cooling of the absorber canister and automatic control devices for the module life testing. The test station provides good flexibility for quick change in operating conditions.

Necessary instrumentation was provided for the measurement of concentration, flow rates, pressure drop, temperature increase of the process air and the cooling air.

All testing was done at atmospheric pressure. The sorbent was regenerated thermally at 150°C with electrical heaters surrounding the absorber units. A large volume tank and a high capacity vacuum pump comprised the vacuum reservoir for vacuum

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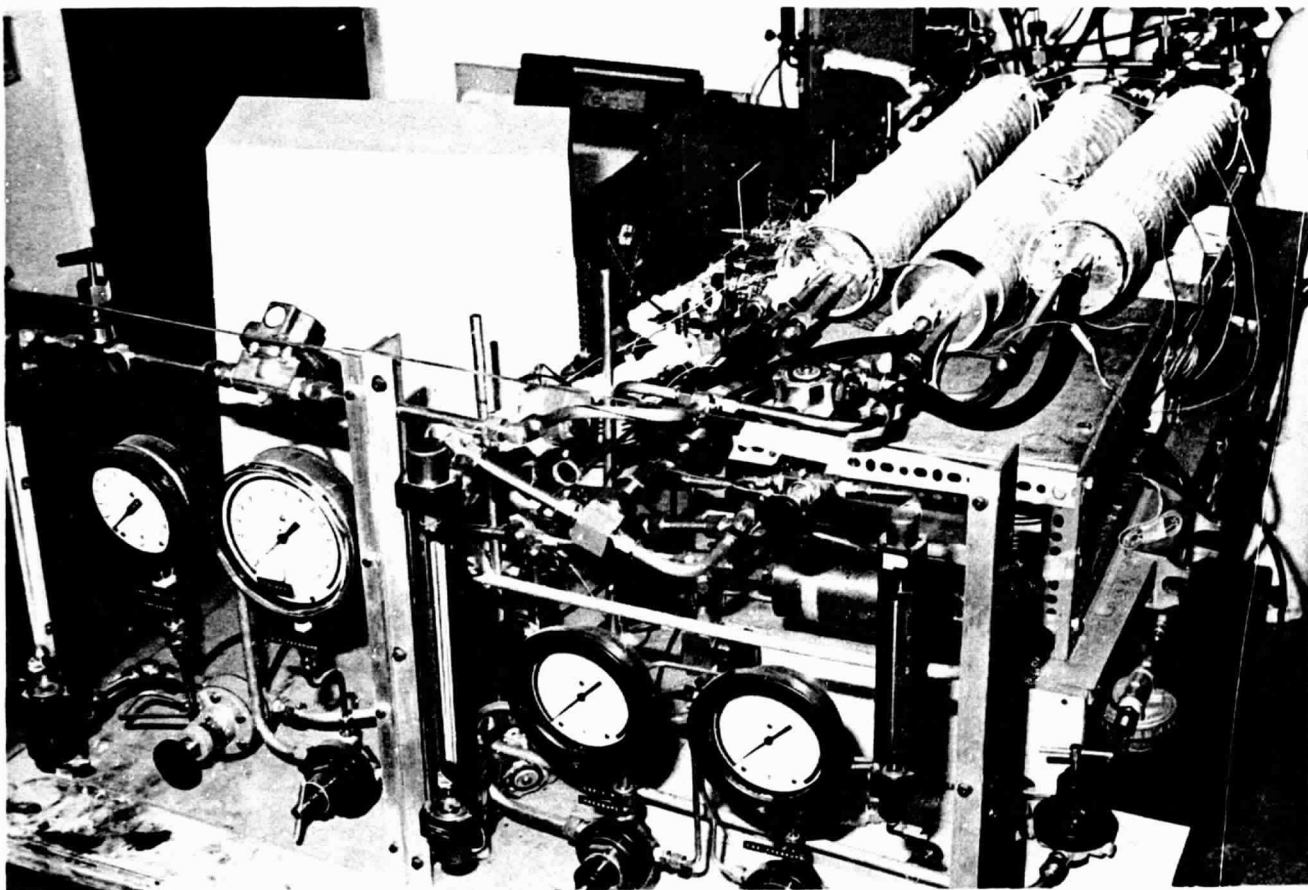
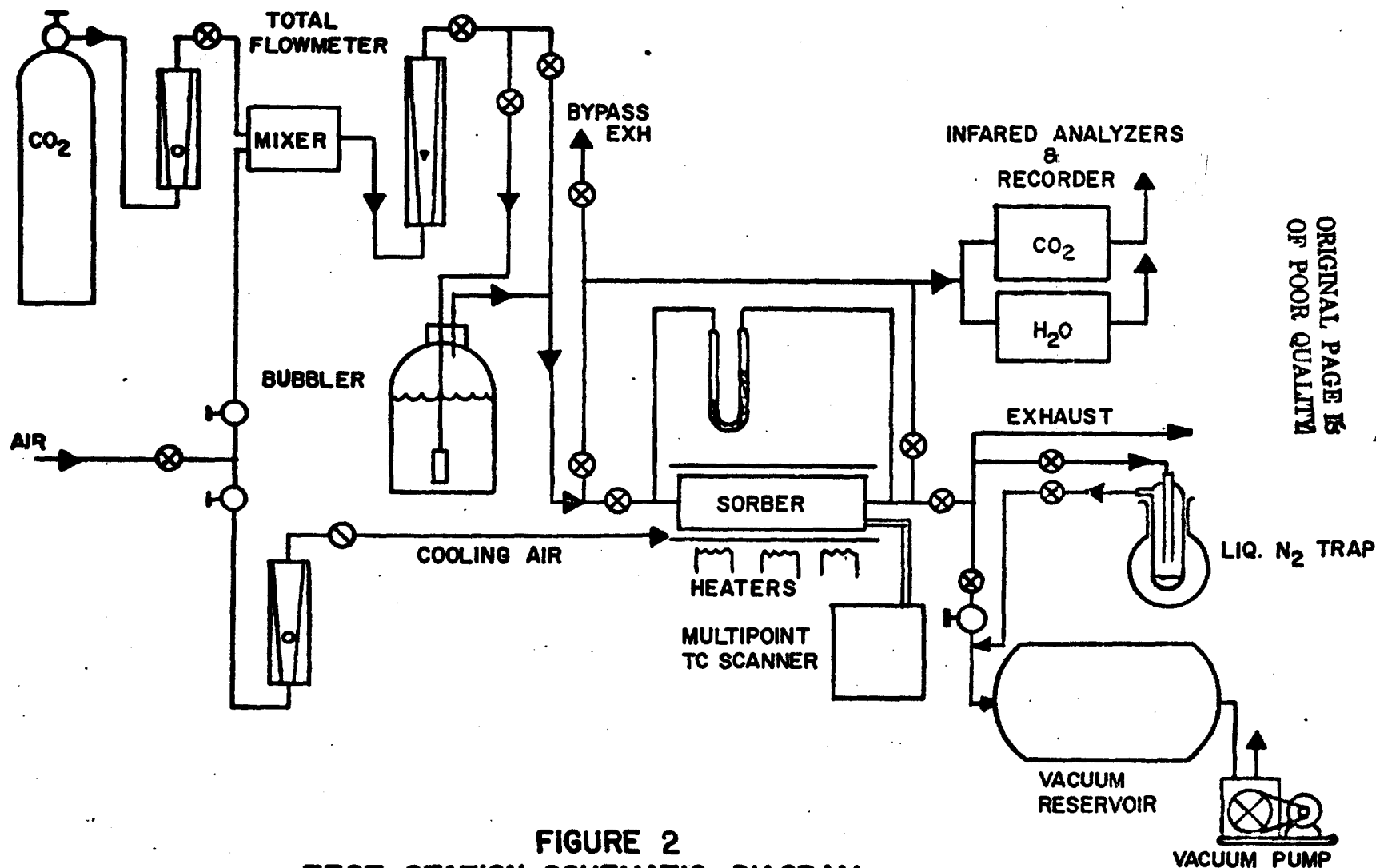


FIGURE 1

PICTORIAL VIEW OF THE CO<sub>2</sub> SORBER MODULE TEST STATION





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**FIGURE 2**  
**TEST STATION SCHEMATIC DIAGRAM—**  
**MODIFIED FOR VACUUM REGENERATION**

regeneration. Fine wire thermocouples were embedded in various zones inside the absorber unit to monitor temperatures. The pressure drop across the absorber was also measured.

The general test conditions applied for absorber testing were derived from the PLSS design specifications (Table 2).

TABLE 2

PLSS Design SpecificationsBasis: 1 Crewman

|                                  |  |
|----------------------------------|--|
| Temperature:                     | 21 - 32°C (70 - 90°F)  |
| Metabolic Rate:                  | Average: 302 Kcal/hr (1200 Btu/hr)<br>Range: 101-504 Kcal/hr (400-2000 Btu/hr) |
| Respiratory Gas:                 | Maximum: 240 liter/min   |
| Flow Rate:                       | Total Press: 4 hr-760  |
| Dew Point:                       | 10-21°C (50-70°F)  |
| Allowable CO <sub>2</sub> Conc.: | Maximum: 5mm Hg  |
| CO <sub>2</sub> Generation Rate: | 1.0 liters/min at 25°C<br>or 108 gms/hr (0.238 lb/hr)                          |
| Mission Length:                  | 8 hours  |
| Coolant:                         | Air or Water   |

#### 4.0 SORBER MODULE DESIGN OPTIMIZATION

Active investigative efforts were made in the direction of optimization of the sorber module design with respect to: heat transfer and temperature control, percent sorber utilization, CO<sub>2</sub> sorption rate, sorber module life and regenerability, power consumption, module weight and volume.

##### 4.1 Isothermal Operation

Earlier research efforts have revealed importance of temperature control on absorption reaction. The reaction is favored by low temperature isothermal operation. Reaction rates observed in cooled canisters were much higher than the uncooled canisters. Complete adiabatic absorption may have a temperature rise of 60-80°C (Table 8). Figure 3 shows a typical temperature profile for uncooled canisters. Initial efforts in sorber module design optimization were directed at active cooling to improve absorber performance and hence, to arrive at optimum L/D ratio.

##### 4.1.1 Active Cooling

Previous canister design was improved and modified to provide for active cooling. Construction of new sorbent canisters is illustrated in Figure 4. The construction is similar to the basic sorber design that evolved in previous study but with the addition of an annular coolant jacket and an axial cooling tube.

Two types of coolants may be used to maintain absorption isothermal: (a) gaseous and (b) liquid. The liquid coolant system has an obvious advantage of better heat

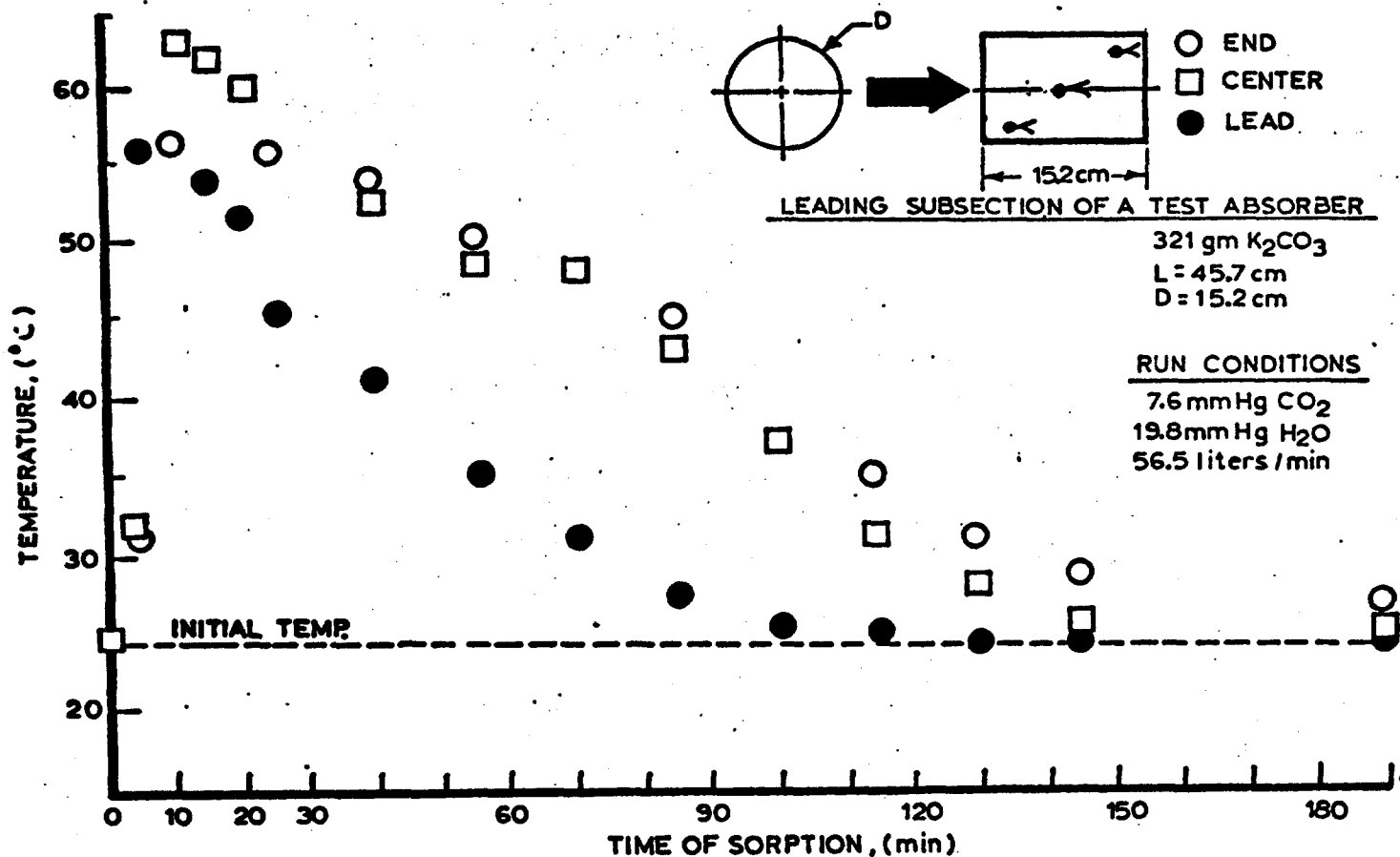
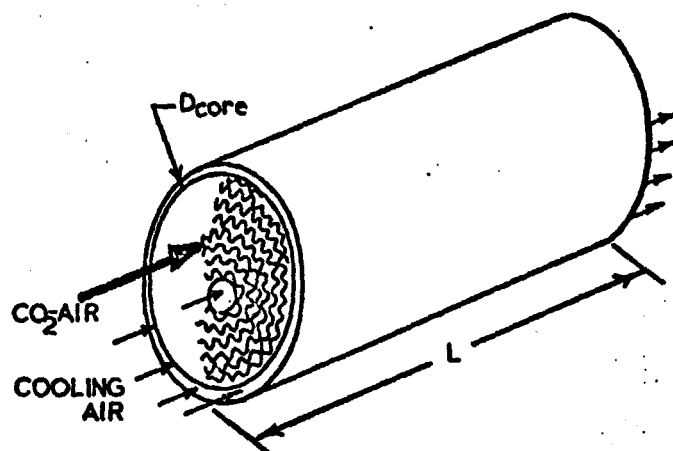


FIGURE 3 TEMPERATURE RISE IN THE UNCOOLED, LEADING ABSORBER SUB-SECTION



379 gm  $K_2CO_3$

$L = 45.7$  cm

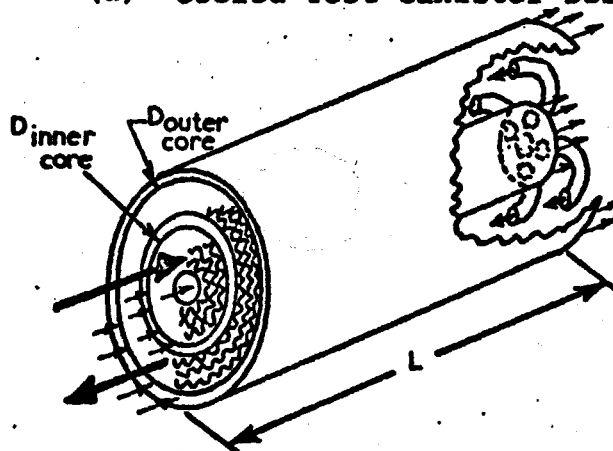
$D = 15.2$  cm

$L/D = 3.01$

Run No: 100 Series

AIR COOLING THROUGH  
0.3 cm ANNULUS AND  
1.3 cm  $\phi$  AXIAL TUBE

(a) Cooled Test Canister Design



364 gm  $K_2CO_3$

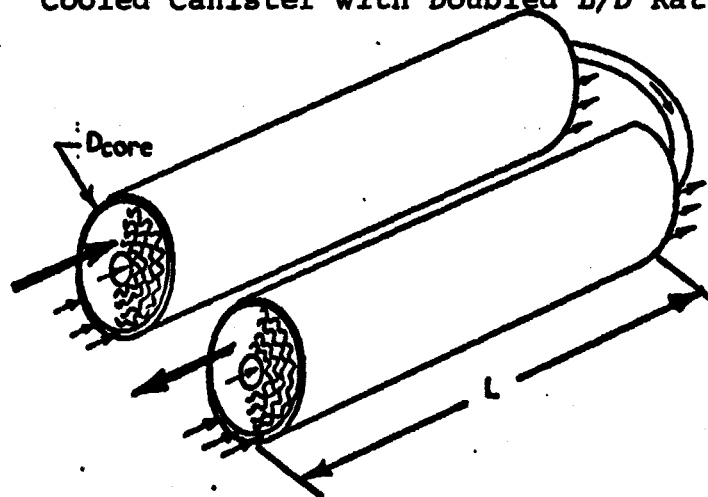
$L = 45.7$  cm

$D_{inner} = 7.6$  cm

$D_{outer} = 15.2$  cm

$L/D_{eff} = 5.88$

(b) Cooled Canister with Doubled  $L/D$  Ratio



348 gm  $K_2CO_3$

$L = 45.7$  cm

$D = 10.2$  cm

$(2L)/D = 8.96$

Run No.: 300 Series

(c) Cooled Canister with Tripled  $L/D$  Ratio

FIGURE 4 VARIOUS ABSORBER TEST UNITS - ACTIVELY COOLED

transfer over gaseous coolants. However, from convenience viewpoint in conjunction with EVA missions, cooling air can be made available with relatively more ease. Hence, only active air cooling was considered in the present studies.

Cooling air was passed through the central and annular jackets to remove exothermic heat of reaction and maintain the sorbent material isothermal. Cooling of the sorber canister in this manner during sorption led to a twofold advantage:

- (a) decreased the rate of loss in sorbent activity over repeated absorption and regeneration cycles by reducing thermal stresses in the sorbent. Table 3 and Table 5 elucidate this improvement. The decay rate of sorbent activity is decreased by approximately 5 to 10 times over uncooled units and
- (b) probably increased the utilization of potassium carbonate over that obtained in the previous study for the same inlet duty as is shown in Figure 5.

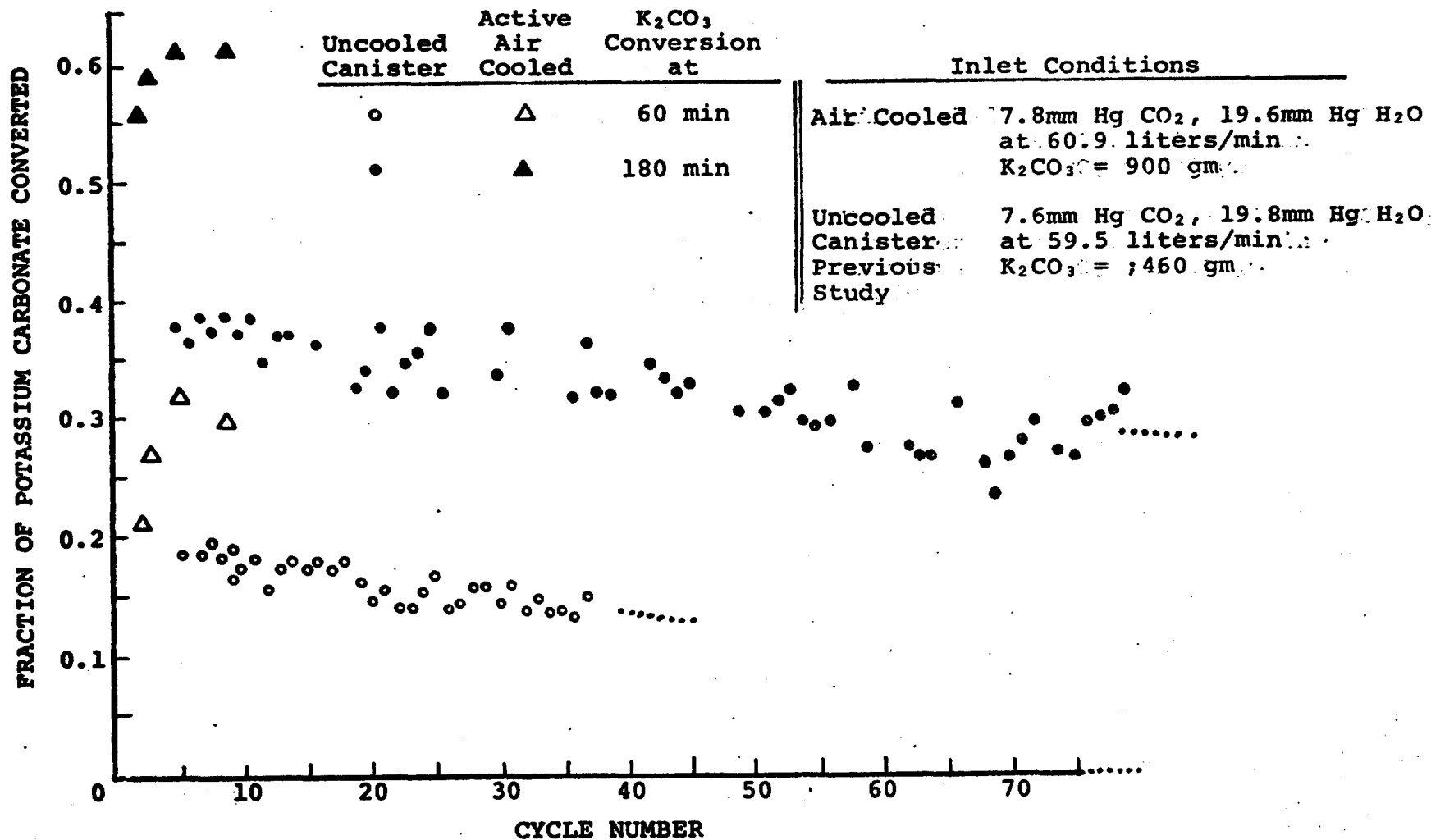
TABLE 3

Cycle Life of Uncooled Canister

Operating Conditions: Inlet conc. of  $\text{CO}_2$  = 7.6 mm Hg  
 Inlet conc. of  $\text{H}_2\text{O}$  = 19.8 mm Hg  
 Sorption Air Flow = 59.5 lit/min.  
 Inlet temperature =  $25 \pm 4^\circ\text{C}$   
 No. of canisters = 1  
 Wt. of  $\text{K}_2\text{CO}_3$  = 1470 gm

| Time<br>of<br>Sorption<br>t<br><br>min | % Utilization<br>of $\text{K}_2\text{CO}_3$ during<br>first cycle | Decay rate of<br>Sorption activity *<br>% $\text{K}_2\text{CO}_3$ utilization drop/cycle |
|--|---|--|
| 30                                     | 10.9  | 0.08   |
| 60                                     | 19.7  | 0.18   |
| 120                                    | 32.1  | 0.21   |
| 180                                    | 39.0  | 0.16   |

\* Decay rate of sorption activity at a given sorption time, t, is defined as average drop in percent carbonate utilization per cycle.



**FIGURE 5 COMPARISON OF COOLED ABSORBER  
 WITH NON-ACTIVELY COOLED UNIT OF PREVIOUS STUDY**



The peak temperature reached in the cooled unit lies in the range of 37 - 45°C, whereas 64°C was reached with the uncooled units. Thus, a substantial reduction in temperature was achieved.

The second step taken to increase sorbent performance was to further aid sorber cooling. The radial position of maximum sorbent temperature was experimentally found between the center cooling hole and the annular jacket. At that position, a 0.3cm wide annular cooling jacket was constructed as shown in Figure 4-b. This divided the sorbent into two cylinders, one inside the other. Testing with this design premitted observation of performance improvement by extra cooling at the point of maximum temperature, and by simple plumbing modifications the L/D ratio could be nearly doubled. The carbon dioxide laden air stream could be made to flow once through each cylindrical core, or be made to enter the center core and then turned around to flow back through the outside core. Unfortunately, this module cross-leaked because of mechanical problems mixing cooling air with carbon dioxide air. This unit may be a good design for isothermal operation.

Although the temperature was significantly reduced with these methods, further reduction from approximately the 37°C range to the 20°C range was not accomplished. The cylindrical sorbent canister radial direction heat transfer is low and limits the removal of heat.

#### 4.2 L/D Ratio

The effect of sorber length to diameter (geometric) ratio on performance was investigated. As shown in Figure 4, test sorber units having different L/D ratios were constructed and evaluated for carbon dioxide removal ( $L/D = 3.01, 5.88, 8.96, \text{ \& } 13.51$ ). These units almost cover the whole range of practical variation of L/D ratio for man pack units. Active cooling with ambient air was employed in each case except in the case of the sorber unit with the L/D ratio of 5.88. This could not be done because of mechanical problems. In all the test units, active cooling of the sorber via an air stream flowing through an annular channel and an axial centerline tube increased the carbon dioxide uptake and decreased the sorber temperature rise. The specific performances of the actively cooled canisters are compared in Figures 6 & 7.

As shown in Figure 6 for the same flow rates, the amount of carbon dioxide removed approaches input amount as inlet concentration of  $\text{CO}_2$  decreases (Run 301 and 312, Run 310 and 311). Similar effect is observed for the decrease in process air flow rate with  $\text{CO}_2$  inlet concentration being constant. As shown in Figure 7, a decrease in space velocity, improves performance by producing lower outlet concentrations of carbon dioxide. However, this also results in decreased utilization of the carbonate.

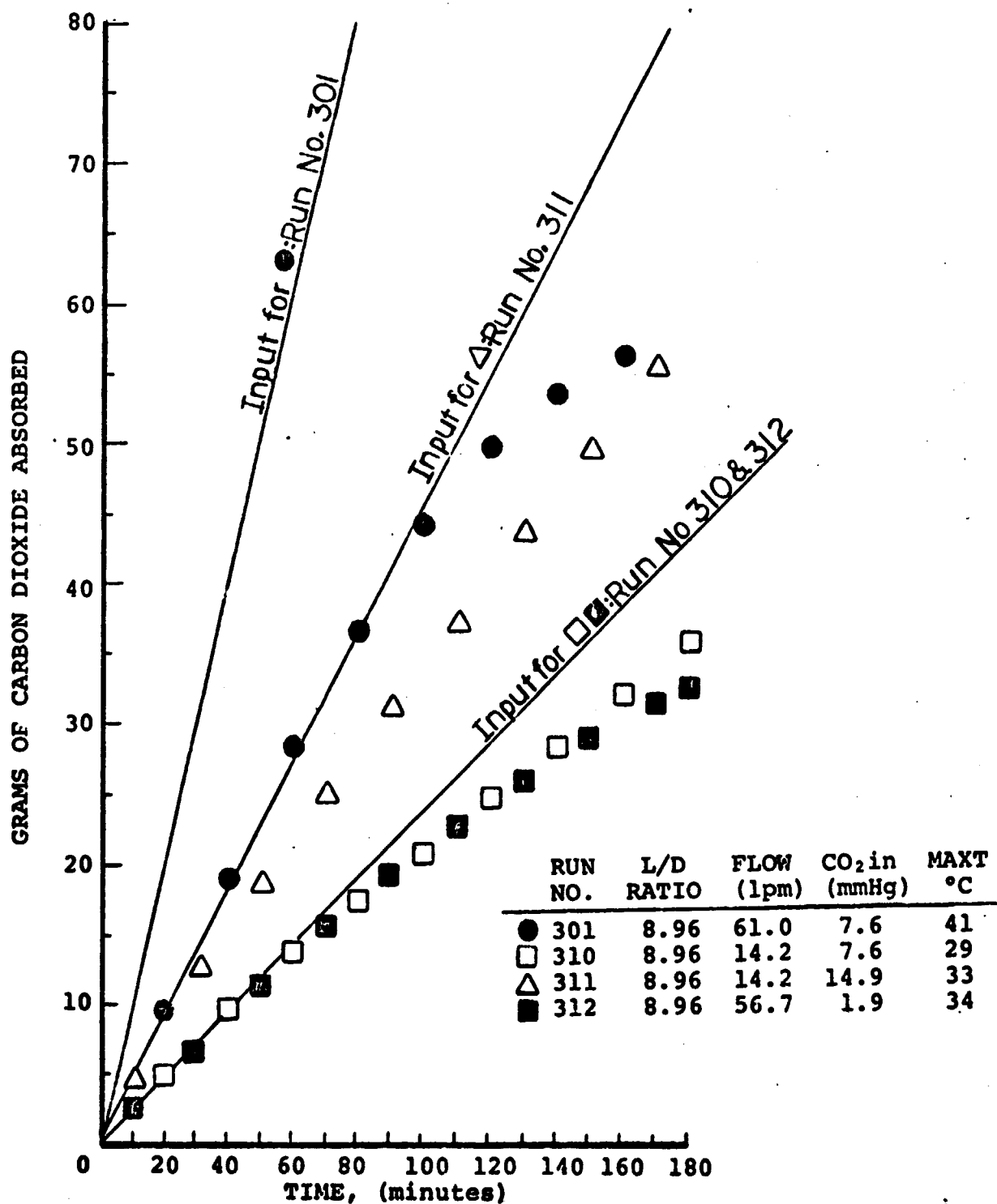


FIGURE 6 CARBON DIOXIDE PICKUP RELATED TO  
INPUT LOAD

| RUN NO. | L/D RATIO | FLOW (lpm) | CO <sub>2</sub> IN (mmHg) | MAXT °C | SPACE VELOCITY* cm/sec |
|---------|-----------|------------|---------------------------|---------|------------------------|
| ○ 109   | 3.01      | 61         | 7.6                       | 49      | 5.6                    |
| ● 301   | 8.96      | "          | "                         | 41      | 12.4                   |
| □ 305   | 8.96      | 29.8       | "                         | 36      | 6.0                    |
| ■ 310   | 8.96      | 14.2       | "                         | 29      | 2.9                    |

\* Space velocity, based on empty cross section area of the canister

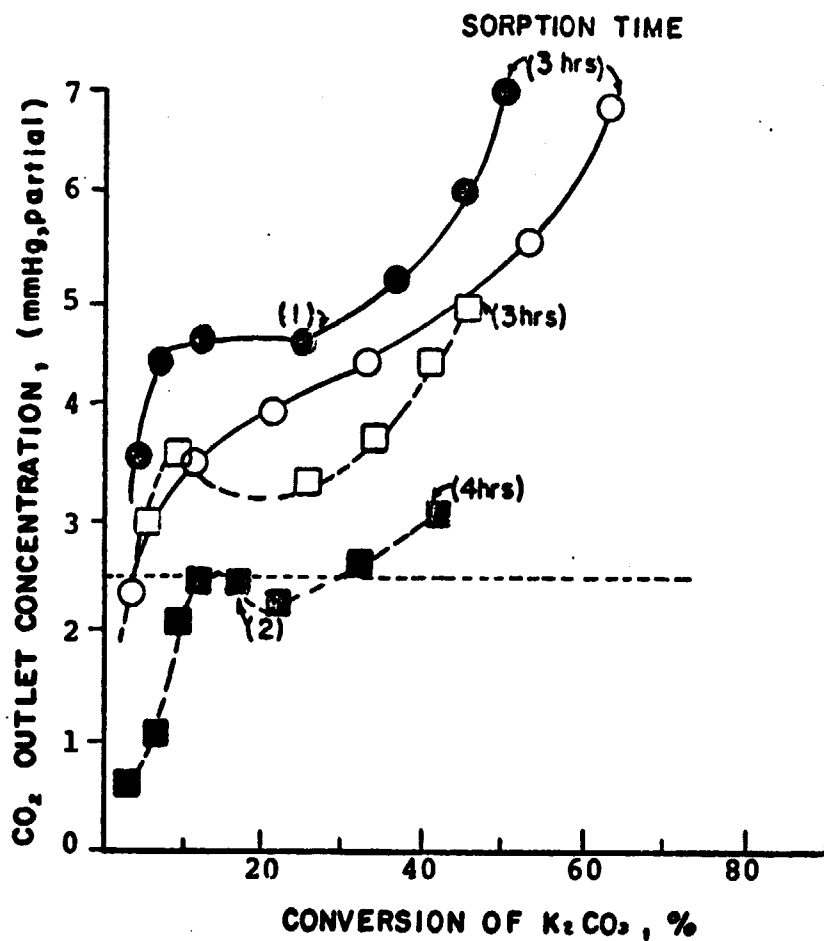


FIGURE 7 OUTLET CARBON DIOXIDE CONCENTRATION AS  
A FUNCTION OF L/D RATIO AND SORBER AIR FLOW

The single canister with its L/D ratio of 3.01 outperformed the other canister with L/D of 8.96. For the equivalent run conditions, the 3.01 canister removes about 15% more carbon dioxide and produces a lower outlet carbon dioxide concentration. However, it contained 31 more grams of potassium carbonate (about 9%). The uncooled canister having L/D of 5.88 performed within 20% of the cooled unit with L/D of 3.01.

In general, the sorbent core diameter to sorbent length ratio affects sorber performance. However, the effect is not exactly like the classic reactor behavior. In typical chemical reactors, the feed is fully converted for a certain L/D value, i.e. long and thin reactors rather than short and fat. Here, however, the L/D ratio affects performance mainly by the transfer of reaction heat out of the system. The larger the sorbent core diameter, the poorer is the heat transfer. Hence, the temperature rises and decreases the sorber capacity. Conversely, the smaller the core is made, the less active material is present per unit area.

Hence, the effect of the sorber temperature rise complicates the optimization of the sorber geometry. A smaller core tested has produced lower temperature rises and somewhat lower capacities than a larger core. The higher ratio canisters perform better, in general, than lower ratio canister. They exhibit a lower temperature rise because this is a shorter heat transfer path to the cooling jacket.

#### 4.3 Radial Heat Transfer

Initial investigations to optimize sorber module design revealed that the key factor to make an excellent sorber is to cool the unit. The radial direction heat transfer resistance is the controlling resistance.

With the present spirally wound construction of the sorbent material and separator, the overall radial conductivity is low because of the low conductivity of the sorbent layer. The corrugated expanded aluminum "screen-like" separator provides excellent heat conduction within a channel between two sorbent layers, but the porous sorbent material hinders the transfer of heat.

An effort was made to decrease the resistance across the sorbent material. A simple solution that would create "heat-short circuits" through the sorbent material was tested. A separator material with sorbent-piercing barbs that could physically contact the adjacent channel separator would create a metal network of heat transfer paths radially out to the cooling jacket.

Various types of expanded aluminum screen-like separator materials were found but none had barbs (or die imperfections) sufficiently long (0.5mm) that could intertwine with adjacent layer material. A special die could be machined to produce such a material.

An alternate, non-ideal method was tried using about five hundred steel pins about 0.5mm in diameter and 5 cm long in one sorber canister. These were inserted into the rolled sorbent core radially. The core was then inserted into the jacketed canister. The contact of the steel pins with the cooling jacket was insufficient for effective heat transfer to the cooling jacket. Improved heat transfer at the wall of the cooling jackets could be achieved with pins that extend through the cooling jacket wall and with brazed or welded contact.

Construction of such systems is complicated and simpler methods were considered evolving into the design choice using a liquid cooled tube array throughout the core area as the simplest and most effective heat removal method. Since radial heat transfer controls the sorbent utilization, it has a good impact in the overall weight and volume of the module. Extensive efforts should be made to improve radial heat transfer.

#### 4.4 Operating Modes

The flow rate to the sorber and the flow rate split into the multitude of channels within the sorber is an important factor for carbon dioxide removal efficiency and sorbent conversion. As mentioned in Section 4.2, the outlet concentration decreases as the flow rate decreases with the inlet concentration remaining fixed. Canister configuration can also affect the radial heat transfer to some extent. A systematic study was undertaken to

evaluate various configurations to aid sorber module design optimization. Various configurations tested were two and three canisters either in series or in parallel. Baffle arrangement employed to ensure proper flow distribution is shown in Figure 8. The process flow diagram for series and parallel canister absorber units is represented by Figure 9.

#### 4.4.1 Series Configuration

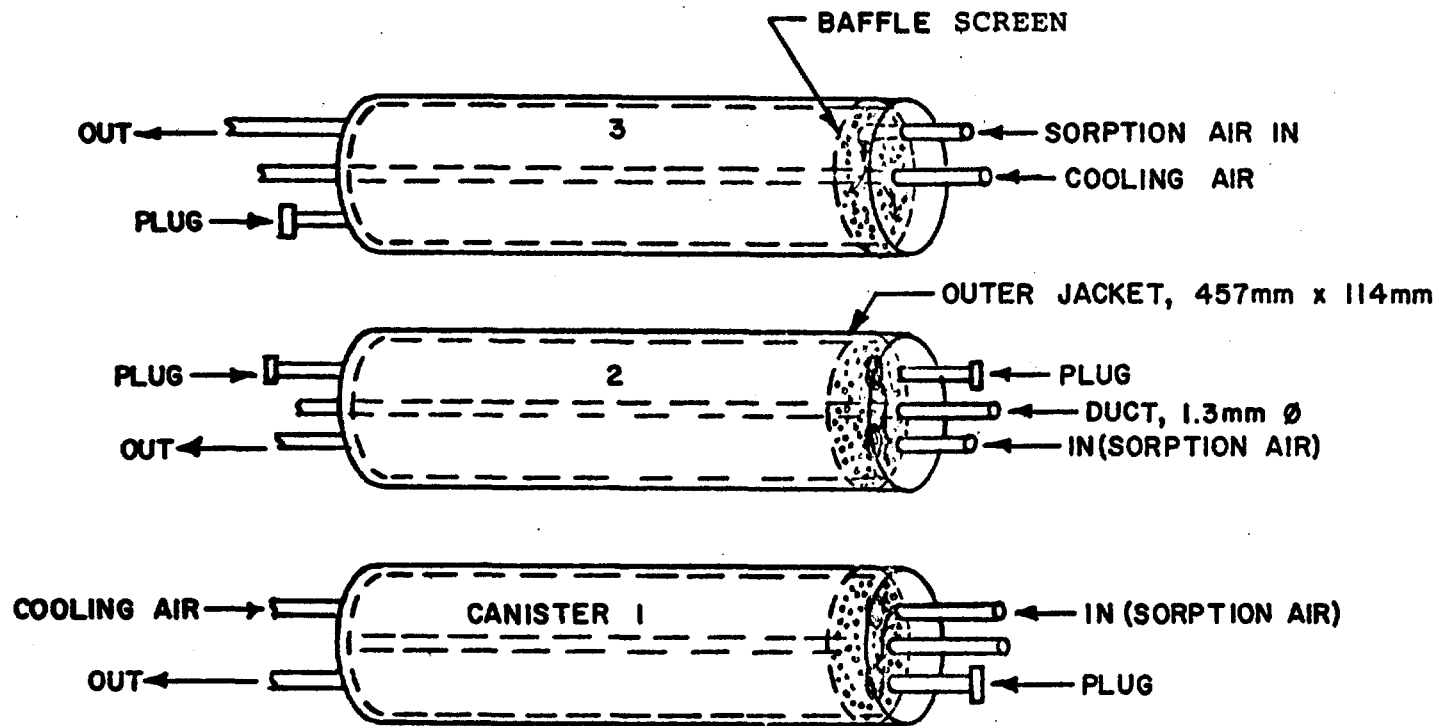
A configuration having two canisters in series maintained low concentration of  $\text{CO}_2$  for only a short period of time (Table 4). Figure 10 shows the outlet carbon dioxide concentration as a function of time for a three canister series absorber set ( $L/D = 13.5$ ) for different total flow rates through the absorber. The runs with flowrates below 17 liters per minute satisfy the 2.6\*mmHg outlet concentration criteria for three, and probably four hours. Three hours of sorption was the arbitrary cut-off point for these test units.

Figure 11(a) presents the carbon dioxide outlet concentration as a function of the potassium carbonate conversion for three canisters in series. For this configuration, the run with 8.5 liters/min flow maintains outlet composition of  $\text{CO}_2$  below 2.6 mmHg throughout the run and achieves conversion 50 percent.

---

\*Criterion of Outlet Conc. of  $\text{CO}_2$  is discussed in Section 6.1.





NOTE: CONNECTIONS SHOWN ARE FOR  
PARALLEL CONFIGURATION.

: BAFFLE SCREEN HAS DEFLECTOR IN  
FRONT OF THE INLET PORT

**FIGURE 8**  
**BAFFLE ARRANGEMENT FOR CANISTERS USED IN SERIES & PARALLEL  
CONFIGURATION.**

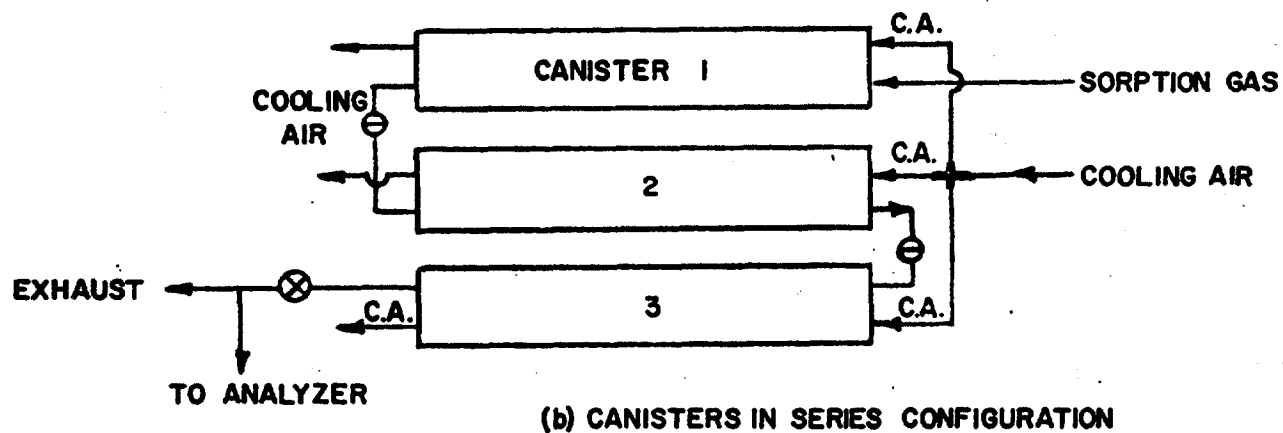
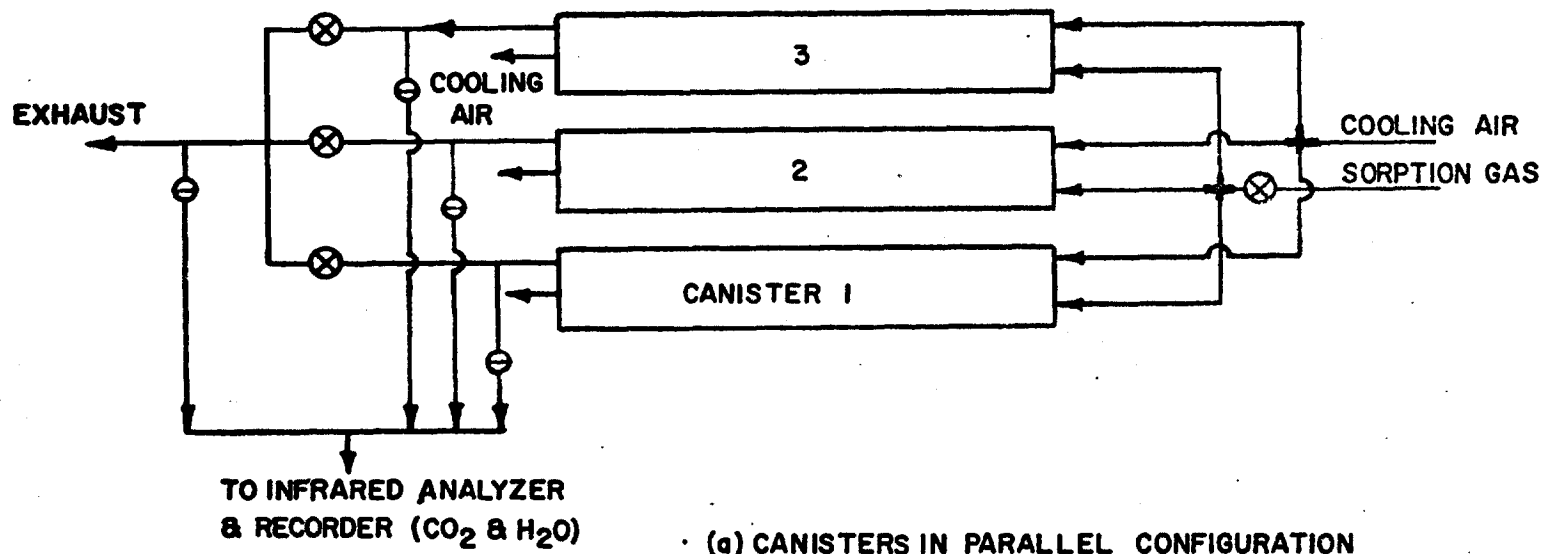


FIGURE 9  
SCHEMATIC FLOW DIAGRAM FOR SERIES & PARALLEL CONFIGURATION

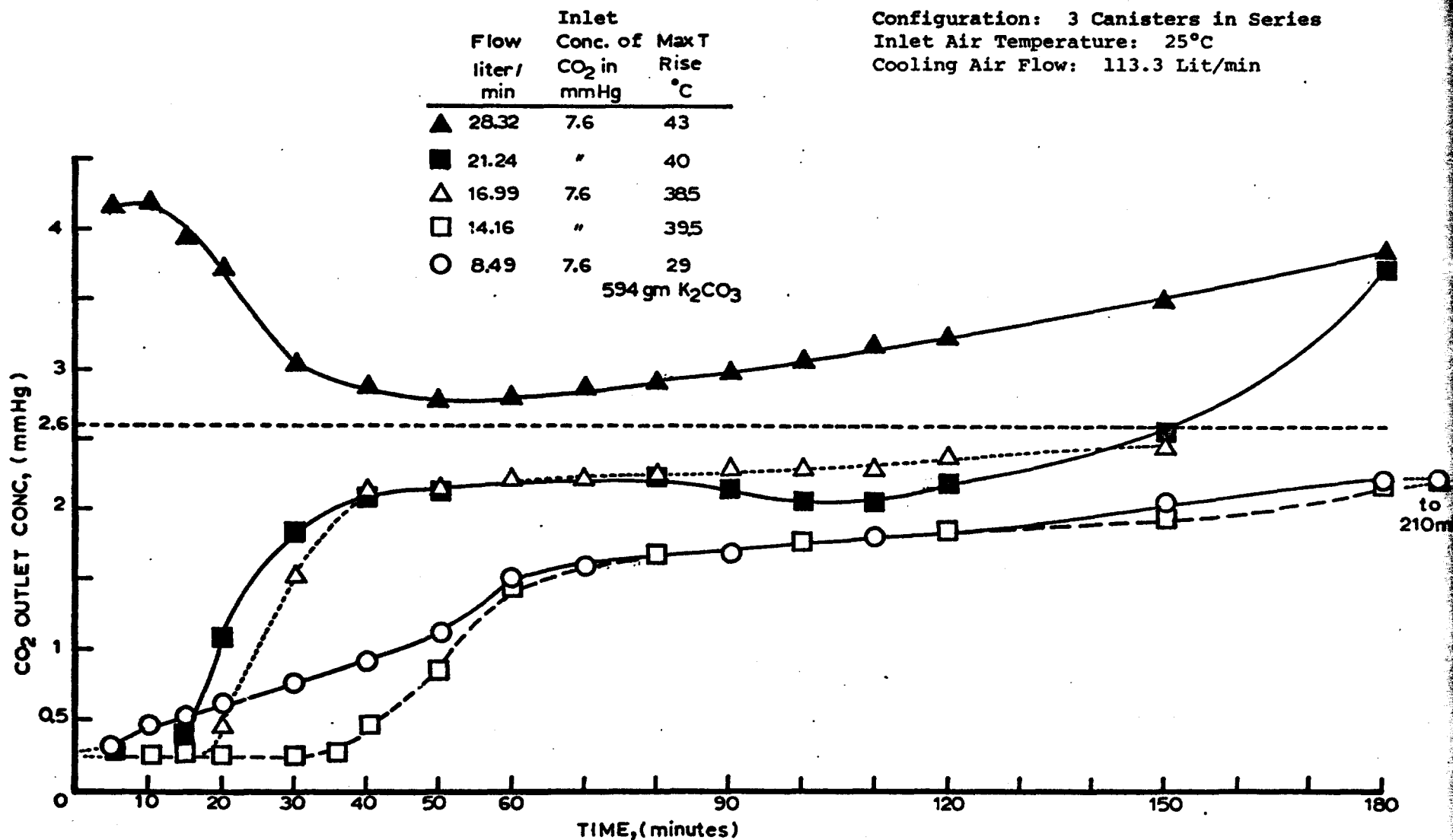
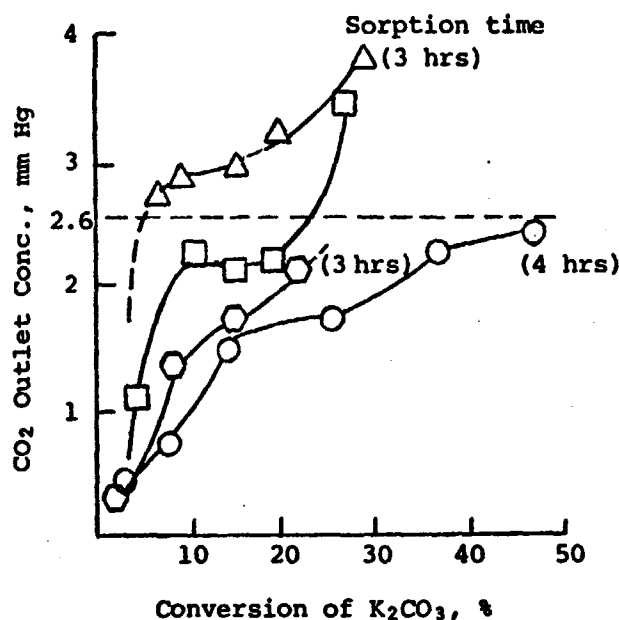


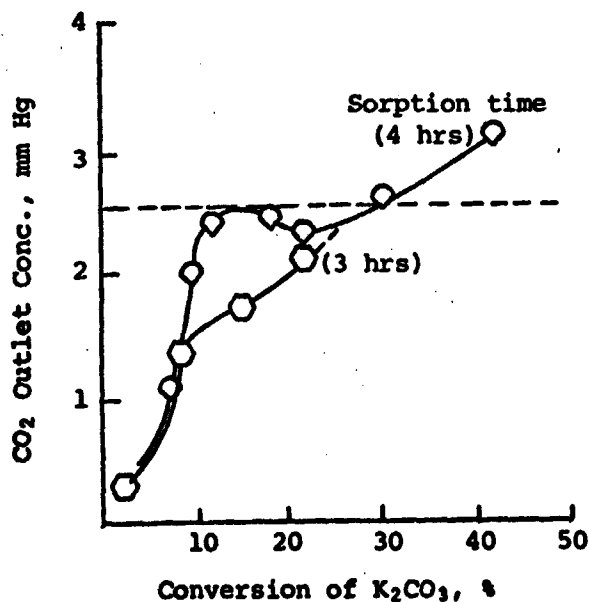
FIGURE 10 Carbon Dioxide Outlet Concentration  
as a Function of Time for Three  
Canister Series Absorber



|   | Inlet Air Flow<br>Lit/min | Inlet CO <sub>2</sub> Conc.<br>mm Hg | Max. Temp. Rise,<br>°C |
|---|---------------------------|--------------------------------------|------------------------|
| ○ | 8.49                      | 7.6                                  | 29.0                   |
| ◊ | 14.16                     | 7.6                                  | 39.5                   |
| □ | 21.24                     | 7.6                                  | 40.0                   |
| △ | 28.32                     | 7.6                                  | 43.0                   |

For all runs, K<sub>2</sub>CO<sub>3</sub> = 594 gms.

(a) Performance of Three Canisters in Series Configuration



| Configuration           | Inlet Air Flow<br>Lit/min | Inlet CO <sub>2</sub> Conc.<br>mm Hg | Amt. K <sub>2</sub> CO <sub>3</sub><br>present<br>gm. |
|-------------------------|---------------------------|--------------------------------------|---|
| ◊ 2 Canisters in Series | 14.16                     | 7.6                                  | 348   |
| ◊ 3 Canisters in Series | 14.16                     | 7.6                                  | 594   |

(b) Two Canister versus Three Canisters in Series

Figure 11 Carbon Dioxide Outlet Concentration as a Function of Potassium Carbonate Conversion

# FOLDOUT FRAME (

TABLE 4. PERFOR

| SR.<br>NO. | OPERATING<br>MODE              | DETAILS OF<br>SORBER MODULE<br>TESTING   | RUN<br>NO. | FLOW,                |                            | PEAK TEMP.<br>REACHED |                      | GENERAL SUMMARY         |  |                                   |     |
|------------|--------------------------------|--|------------|----------------------|----------------------------|-----------------------|----------------------|-------------------------|--|-----------------------------------|-----|
|            |                                |  |            | SORPTION<br>lit/min. | COOLING<br>AIR<br>lit/min. | T<br>°C               | AT TIME<br>t<br>min. | TIME<br>min.            | OUTLET<br>CO <sub>2</sub><br>CONCN.<br>m.m. Hg | CO <sub>2</sub><br>REMOVED<br>gm. | CON |
|            |                                |  |            |                      |                            |                       |                      |                         |  |                                   |     |
| I          | Two canisters<br>in series     | K <sub>2</sub> CO <sub>3</sub> = 348.2 gm,<br>L = 45.7 c.m./canister,<br>Core dia. = 10.2 c.m.,<br>Inlet CO <sub>2</sub> : 1%<br>Temp. 25°C                                      | 302        | 29.8                 | 64.6                       | 40.0                  | 30                   | 60<br>120<br>180        | 3.34<br>3.69<br>5.16                           | 19.9<br>39.1<br>53.6              |     |
|            |                                |  | 301        | 60.9                 | 64.6                       | 40.6                  | 15                   | 60<br>120<br>160        | 4.69<br>6.06<br>7.10                           | 28.3<br>50.0<br>56.2              |     |
| II         | Two canisters<br>in parallel   | ———— " ————  | 304        | 29.8                 | 64.6                       | 40.6                  | 50                   | 60<br>120<br>180        | 3.92<br>4.17<br>5.31                           | 19.0<br>35.9<br>48.9              |     |
| III        | Three canisters<br>in series   | K <sub>2</sub> CO <sub>3</sub> = 594.6 gm<br>47.8% avg. carbonate<br>in sorbent,<br>Core dia. = 10.2 c.m.<br>L = 45.7 c.m./canister<br>Inlet CO <sub>2</sub> : 1%<br>Temp.: 25°C | 407        | 14.2                 | 113.3                      | 38.9                  | 50                   | 60<br>120<br>180        | 1.44<br>1.78<br>2.13                           | 15.2<br>27.6<br>39.6              |     |
|            |                                |  | 408        | 21.2                 | 113.3                      | 39.4                  | 30                   | 60<br>120<br>180        | 2.20<br>2.17<br>3.50                           | 19.0<br>35.9<br>50.7              |     |
|            |                                |  | 403        | 28.3                 | 113.3                      | 42.8                  | 50                   | 60<br>120<br>180        | 2.81<br>3.23<br>3.80                           | 17.9<br>37.2<br>54.4              |     |
| IV         | Three canisters<br>in parallel | ———— " ————  | 1          | 14.2                 | 85.0                       | 40.6                  | 60                   | 60<br>120<br>180<br>240 | 1.47<br>1.88<br>2.35<br>2.63                   | 13.4<br>25.8<br>37.4<br>48.2      |     |
|            |                                |  |            |                      |                            |                       |                      | 300<br>390              | 2.81<br>3.68                                   | 58.7<br>72.9                      |     |
|            |                                |  |            |                      |                            |                       |                      | 60<br>120<br>180        | 2.39<br>2.86<br>3.08                           | 18.5<br>34.4<br>49.4              |     |
|            |                                |  |            |                      |                            |                       |                      | 240<br>320              | 3.60<br>4.26                                   | 63.2<br>78.8                      |     |
|            |                                |  | 2          | 21.2                 | 85.0                       | 47.2                  | 70                   | 60<br>120<br>180        | 2.39<br>2.86<br>3.08                           | 18.5<br>34.4<br>49.4              |     |
|            |                                |  |            |                      |                            |                       |                      | 240<br>320              | 3.60<br>4.26                                   | 63.2<br>78.8                      |     |
|            |                                |  |            |                      |                            |                       |                      | 60<br>120<br>180        | 2.48<br>3.17<br>3.69                           | 25.3<br>45.5<br>63.5              |     |
|            |                                |  |            |                      |                            |                       |                      | 240<br>335              | 4.21<br>4.86                                   | 79.3<br>100.4                     |     |
|            |                                |  | 4          | 28.3                 | 85.0                       | 47.8                  | 50                   | 60<br>120<br>180        | 2.48<br>3.17<br>3.69                           | 25.3<br>45.5<br>63.5              |     |
|            |                                |  |            |                      |                            |                       |                      | 240<br>335              | 4.21<br>4.86                                   | 79.3<br>100.4                     |     |
|            |                                |  |            |                      |                            |                       |                      | 60<br>120<br>180        | 2.48<br>3.17<br>3.69                           | 25.3<br>45.5<br>63.5              |     |
|            |                                |  |            |                      |                            |                       |                      | 240<br>335              | 4.21<br>4.86                                   | 79.3<br>100.4                     |     |

8. PERFORMANCE COMPARISON OF SORBER MODULES WITH DIFFERENT CONFIGURATIONS

| PERFORMANCE                 |  |  |   |  |  |  |  | REMARKS  |
|-----------------------------|--|--|---|--|--|--|--|--|
| SUMMARY                     |  | PERFORMANCE AT CO <sub>2</sub> OUTLET CONCN. OF 2.6 m.m.Hg |   |  | PERFORMANCE AT CO <sub>2</sub> OUTLET CONCN. OF 5.0 m.m.Hg |  |  |  |
| CO <sub>2</sub> REMOVED gm. | CONVERSION OF K <sub>2</sub> CO <sub>3</sub> , % | TIME min.  | CO <sub>2</sub> REMOVED gm.                 | CONVERSION OF K <sub>2</sub> CO <sub>3</sub> , % | TIME min.  | CO <sub>2</sub> REMOVED gm.            | CONVERSION OF K <sub>2</sub> CO <sub>3</sub> , % |  |
| 9.9                         | 17.9   | 15   | 5.64  | 5.1  | 175  | 52.6                                   | 47.4   | Flow distribution: Good  |
| 9.1                         | 35.3   |  |   |  |  |  |  |  |
| 9.6                         | 48.3   |  |   |  |  |  |  |  |
| 9.3                         | 25.5   |  | Mostly above 2.6 m.m. Hg for the whole run  |  |  | 80                                     | 36.9   | 33.3   |
| 9.0                         | 45.0   |  |   |  |  |  |  |  |
| 9.2                         | 50.6   |  |   |  |  |  |  |  |
| 9.0                         | 17.1   | 18   | 7.1   | 6.4  | 160  | 45.1                                   | 40.6   | Flow distribution: Fair  |
| 9.9                         | 32.3   |  |   |  |  |  |  |  |
| 9.9                         | 44.0   |  |   |  |  |  |  |  |
| 9.2                         | 8.0  |  | Below 2.6 m.m. Hg, throughout the run       |  |  | Below 5.00 m.m. Hg, throughout the run |  | Flow distribution: Good  |
| 9.6                         | 14.6   |  |   |  |  |  |  |  |
| 9.6                         | 20.9   |  |   |  |  |  |  |  |
| 9.0                         | 10.0   | 145  |   | 22.6   |  |  |  |  |
| 9.9                         | 19.0   |  |   |  |  |  |  |  |
| 9.7                         | 26.8   |  | Mostly above 2.6 m.m. Hg throughout the run |  |  |  |  |  |
| 9.9                         | 9.5  |  |   |  |  |  |  |  |
| 9.2                         | 19.6   |  |   |  |  |  |  |  |
| 9.4                         | 28.7   |  |   |  |  |  |  |  |
| 9.4                         | 7.1  | 220  | 44.6  | 23.5   |  | Below 5.0 m.m. Hg, throughout the run  |  | Flow distribution: Fair<br>Less cooling air flow than that in series canisters |
| 9.8                         | 13.6   |  |   |  |  |  |  |  |
| 9.4                         | 19.7   |  |   |  |  |  |  |  |
| 9.2                         | 25.4   |  |   |  |  |  |  |  |
| 9.7                         | 31.0   |  |   |  |  |  |  |  |
| 9.9                         | 38.4   |  |   |  |  |  |  |  |
| 9.5                         | 9.8  | 90   | 26.7  | 14.1   |  |  |  |  |
| 9.4                         | 18.2   |  |   |  |  |  |  |  |
| 9.4                         | 26.0   |  |   |  |  |  |  |  |
| 9.2                         | 33.3   |  |   |  |  |  |  |  |
| 9.8                         | 41.6   | 70   | 28.9  | 15.2   |  |  |  |  |
| 9.3                         | 13.4   |  |   |  |  |  |  |  |
| 9.5                         | 24.0   |  |   |  |  |  |  |  |
| 9.5                         | 33.5   |  |   |  |  |  |  |  |
| 9.3                         | 41.8   |  |   |  |  |  |  |  |
| 9.4                         | 53.0   |  |   |  |  |  |  |  |

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The best run from the two canister absorber set is superimposed in Figure 11b for comparison with three canisters in series. Adding an additional canister improved the conversion and reduced the outlet carbon dioxide concentration as is indicated by the runs at 14.2 liters per minute flow.

#### 4.4.2 Parallel Configuration

The two canisters in parallel configurations like two canisters in series could not produce low concentrations of CO<sub>2</sub> for a long time (Table 4). Test results of three canisters in parallel unit are presented in Figures 12 and 13. This configuration does produce CO<sub>2</sub> outlet concentrations below the required limit as well as achieve conversions higher than 50%.

It is interesting to note that in Figure 13. Run No. 2 overlaps with Run No. 4. This indicates that for the same sorbent utilization level, Run No. 4 maintains the same outlet concentration of CO<sub>2</sub> for a longer period of time than Run No. 2.

#### 4.4.3 Series versus Parallel Configuration

Table 4 elucidates relative performance of the various configurations tested. Important parameters for comparison are time sorber maintained permissible outlet concentration of carbon dioxide, and percent conversion of potassium carbonate at that time. Final size of the sorber

CONFIGURATION: 3 CANISTERS IN PARALLEL  
 CO<sub>2</sub> INLET CONCENTRATION: 7.6 MM. Hg.  
 TEMPERATURE: 25°C.  
 COOLING AIR FLOW: 84.95 LIT/MIN.  
 (28.32 LIT/MIN. / CANISTER)

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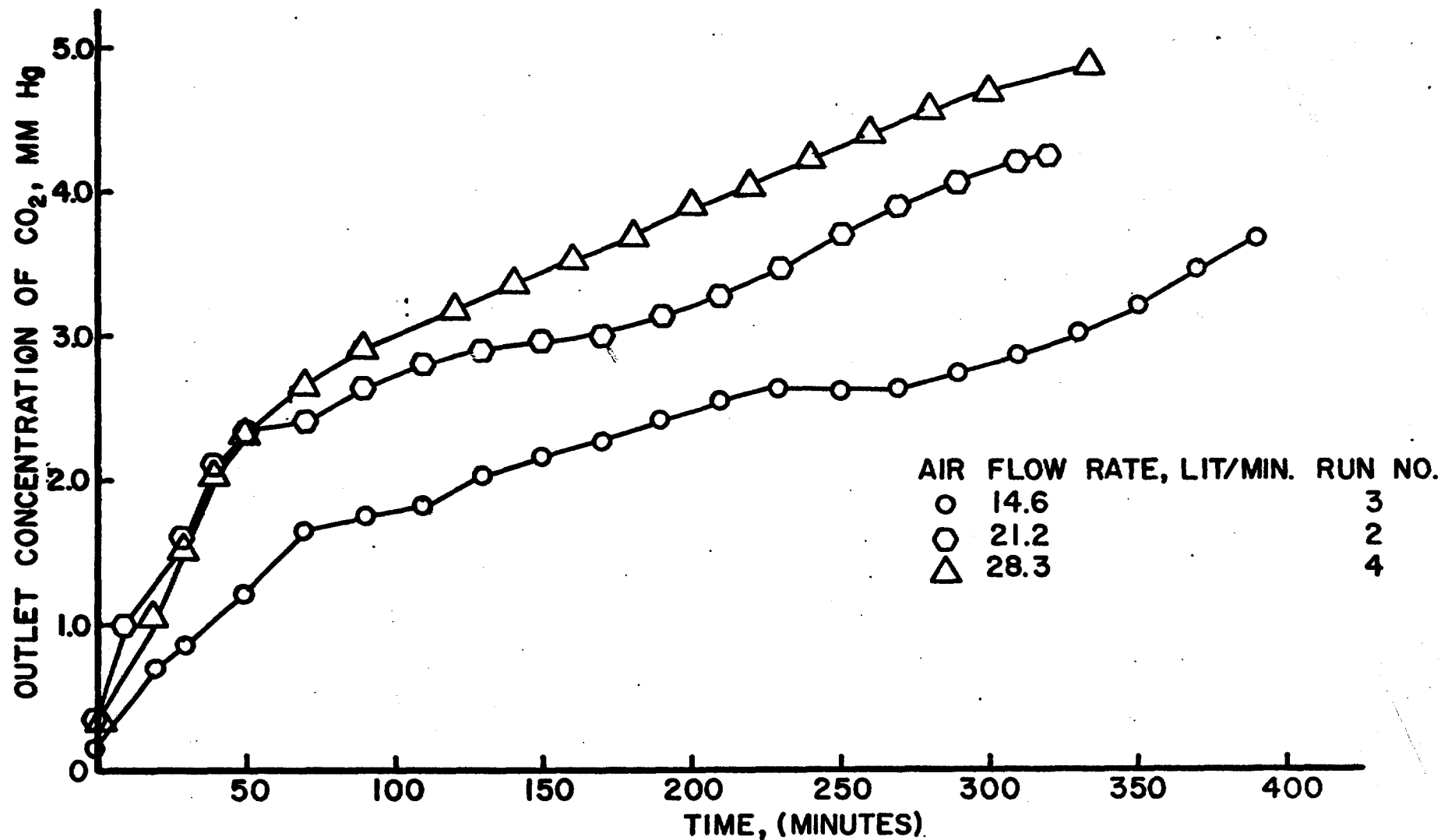
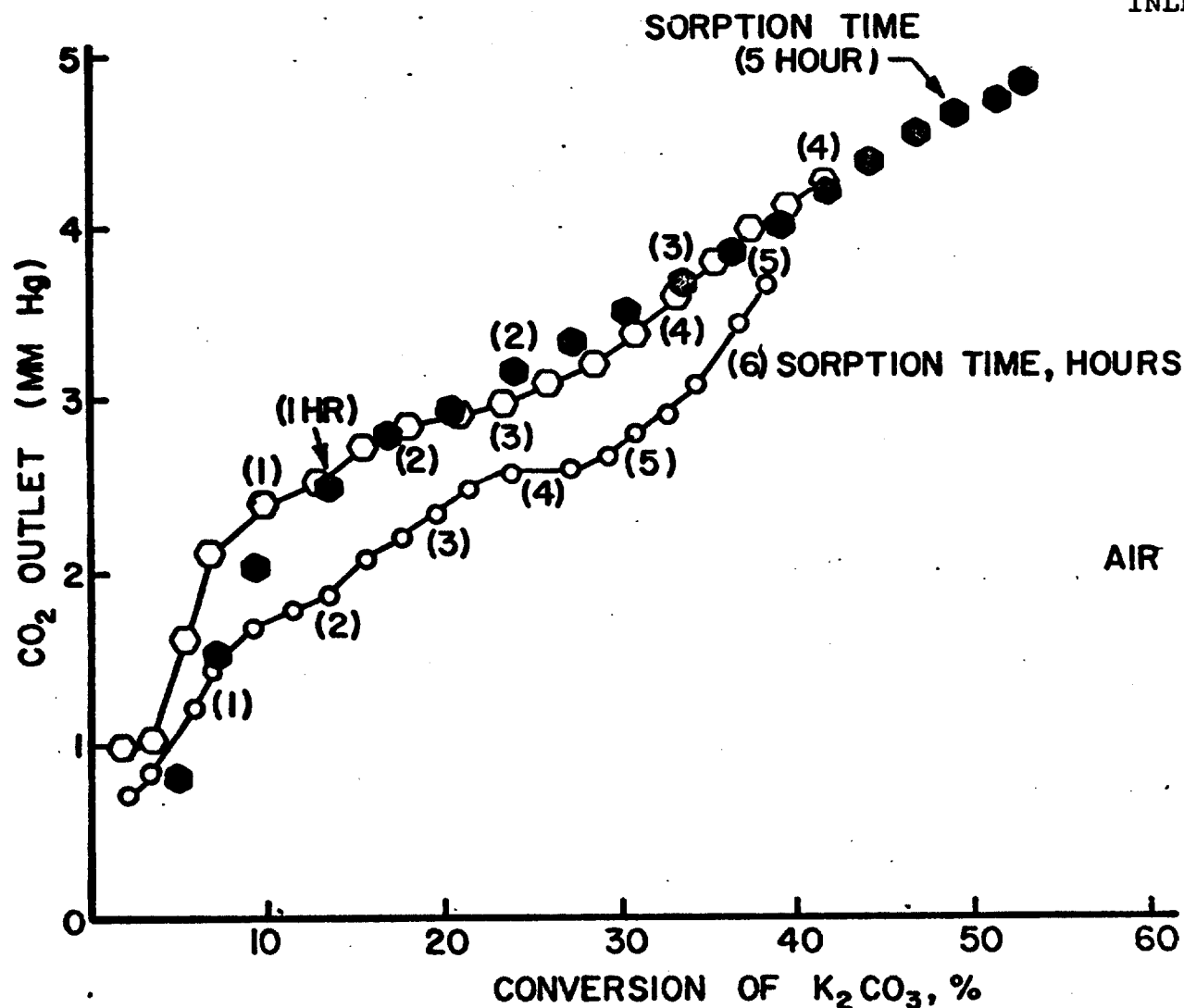


FIGURE 12, CO<sub>2</sub> OUTLET CONC. AS A FUNCTION OF SORPTION TIME





CONFIGURATION: 3 CANISTERS IN  
PARALLEL  
CO<sub>2</sub> INLET CONC. = 7.6 mm Hg  
INLET TEMPERATURE = 25°C  
COOLING AIR FLOW = 84.95 LIT/  
(28.32 LIT/MIN./  
CANISTER)

| AIR FLOW RATE, LIT/MIN | RUN NO. |
|------------------------|---------|
| ○ 14.16                | 3       |
| ○ 21.24                | 2       |
| ● 28.32                | 4       |

FIGURE 13 CO<sub>2</sub> OUTLET CONC. AS FUNCTION OF K<sub>2</sub>CO<sub>3</sub> CONVERSION (Parallel Canisters)

CO<sub>2</sub> Inlet Concentration: 7.6 mm Hg  
Inlet Air Temperature: 25°C  
Cooling Air Flow: 85 Lit/min. for Parallel Canisters  
113 Lit/min. for Series Canisters  
Inlet Air Flow: 21.2 Lit/min.

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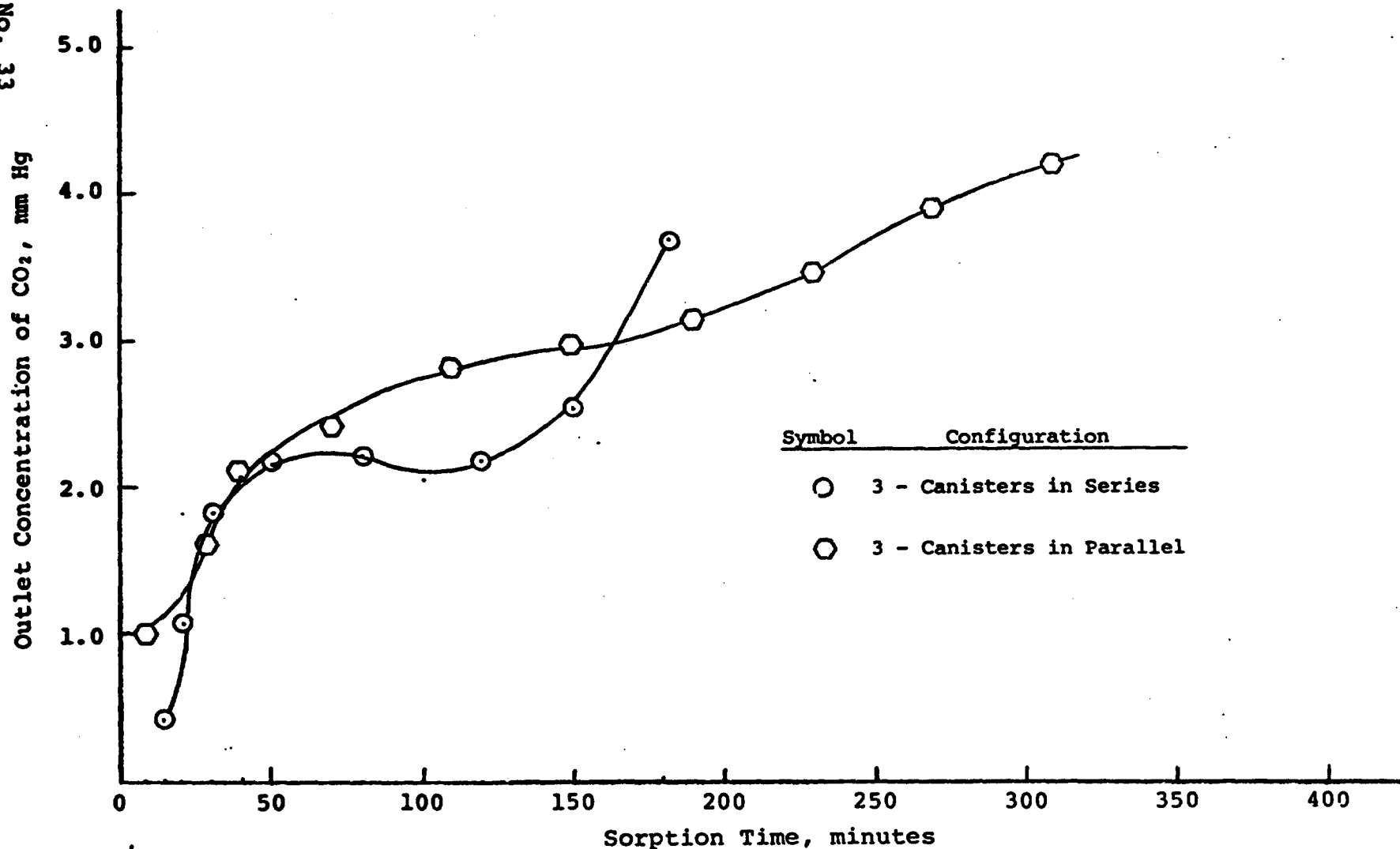


FIGURE 13b Series versus Parallel Configuration

unit is greatly influenced by these two parameters.

Permissible outlet CO<sub>2</sub> concentration is taken as 2.6 mm Hg and 5.0 mm Hg as discussed later.

It is obvious from Table 4 that a sorber unit having two canisters either in series or in parallel does not produce acceptable performance. For the three canister units, performance is similar both in series and in parallel units except that the 3 canisters in parallel produces lower outlet concentration for a longer time.

Though the cooling air flow in the parallel canister sorber was about 75% of the flow used in the series canister sorber, slightly higher conversion levels are achieved in the parallel configuration. Peak temperatures reached in parallel canisters are also quite comparable with the series canister unit. This may be due to improved heat transfer conditions. As shown in Section VI, power requirements would be somewhat lower in the parallel unit. With improved flow distribution and better radial heat transfer, parallel configurations appear to be more promising.

#### 4.5 Vacuum Regeneration

Desorption of carbon dioxide can be accomplished thermally by raising the temperature of the canister to 150°C at ambient pressure. Thermal regeneration is suitable only at base-ship and hence, the size of such a sorber module corresponds to the duty of one complete EVA mission. As mentioned in our previous reports, the size of carbon dioxide absorber for PLSS application

can be greatly reduced if the unit operates on the principle of simultaneous absorption and regeneration. In space, absolute vacuum is available, which can be conveniently used to improve the sorber module design. Vacuum regeneration alone or combined thermal and vacuum regeneration will have good implication on sorber module capacity.

The previous study, in which regeneration under vacuum alone was tried, indicated that the temperature of the sorbent bed decreases with time. This reduces the regeneration rate. Also, the vacuum used was quite coarse, usually between 50-100 mmHg. As shown in the next paragraph, the thermal regeneration with very low vacuum does have good potential.

Figure 14 shows a plot of equilibrium partial pressure of  $\text{CO}_2$  for  $\text{K}_2\text{CO}_3/\text{KHCO}_3$  system. At  $150^\circ\text{C}$ , the partial pressure of carbon dioxide is about 6700 mmHg and hence, the system easily regenerates at atmospheric pressure in reasonable time. At room temperature, the equilibrium partial pressure of  $\text{CO}_2$  is about 1.5 mmHg. If the system is to regenerate at room temperature, the operating pressure should be well below 1.5 mmHg. As carbon dioxide and water start desorbing due to dissociation of potassium bicarbonate, the heat of desorption will reduce the temperature of the sorber. This would slow down the regeneration rate. A better compromise will be to provide heat of reaction by a heater wound spirally with sorbent in the sorbent bed.

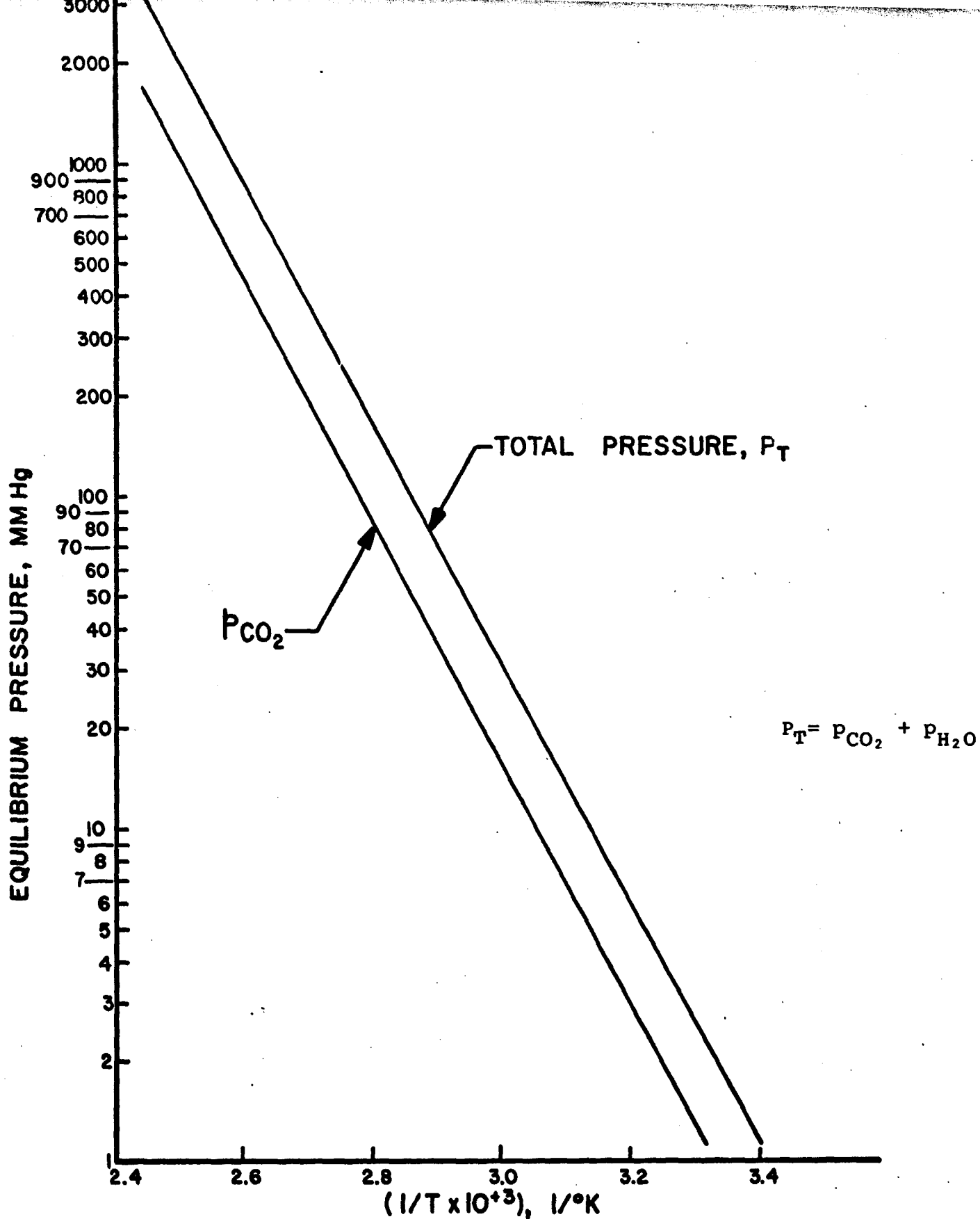


FIGURE 14  
EQUILIBRIUM PARTIAL PRESSURE FOR  $CO_2$  ABSORPTION

Preliminary results of thermal regeneration and vacuum regeneration with heat application are compared in Table 4b. To study the ultra low vacuum conditions in the laboratory, vacuum regeneration was carried out at a coarse vacuum of 50 mmHg and 120°C. Under ordinary thermal desorption at 120°C, it takes quite a long time to get appreciable regeneration. In two hours of combined vacuum and thermal regeneration at 120°C resulted in almost the same extent of reactivation as that obtained by thermal regeneration at 150°C. A schematic diagram of the test station modified for vacuum regeneration is presented in Figure 2. A fine vacuum could be attained by condensing the released water and carbon dioxide in a liquid nitrogen trap, thereby reducing the load on the vacuum pump. Incorporation of a liquid nitrogen trap arrangement is also shown in Figure 2.

In order to arrive at the most realistic size of sorber module, vacuum regeneration at ultra low vacuum should be explored to a greater depth.

#### 4.6 Prehumidification and Rate of Absorption

Few tests were performed to study dependence of rate of CO<sub>2</sub> absorption on the extent of free water absorption. As shown in Figure 14-b, Run 105 saw about 90 minutes of contact with wet air prior to the carbon dioxide inlet, whereas no prehumidification was employed in Run 101. Runs 101 and 105 reveal an important fact in terms of reaction rate, sorber outlet CO<sub>2</sub> concentration and temperature rise. For the first 80 minutes of the sorption time, Run 105 maintained considerably higher reaction rate and lower CO<sub>2</sub> outlet concentration than

Table 4b

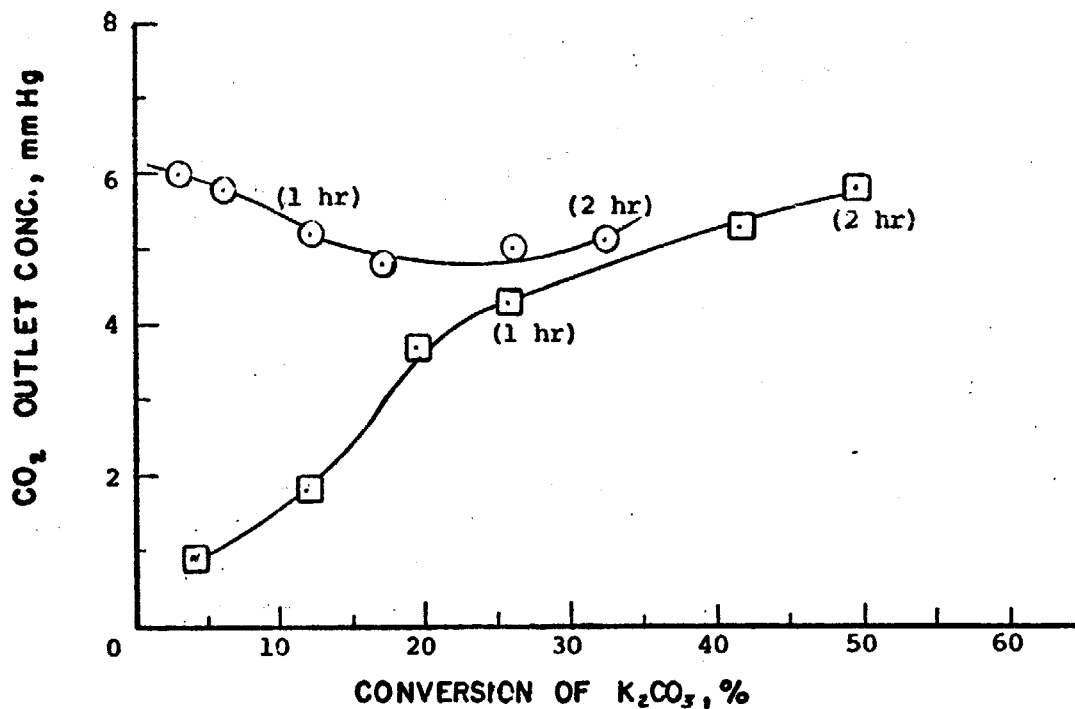
Thermal Regeneration versus Combined  
Vacuum and Thermal Regeneration

Absorption Conditions for all the runs:

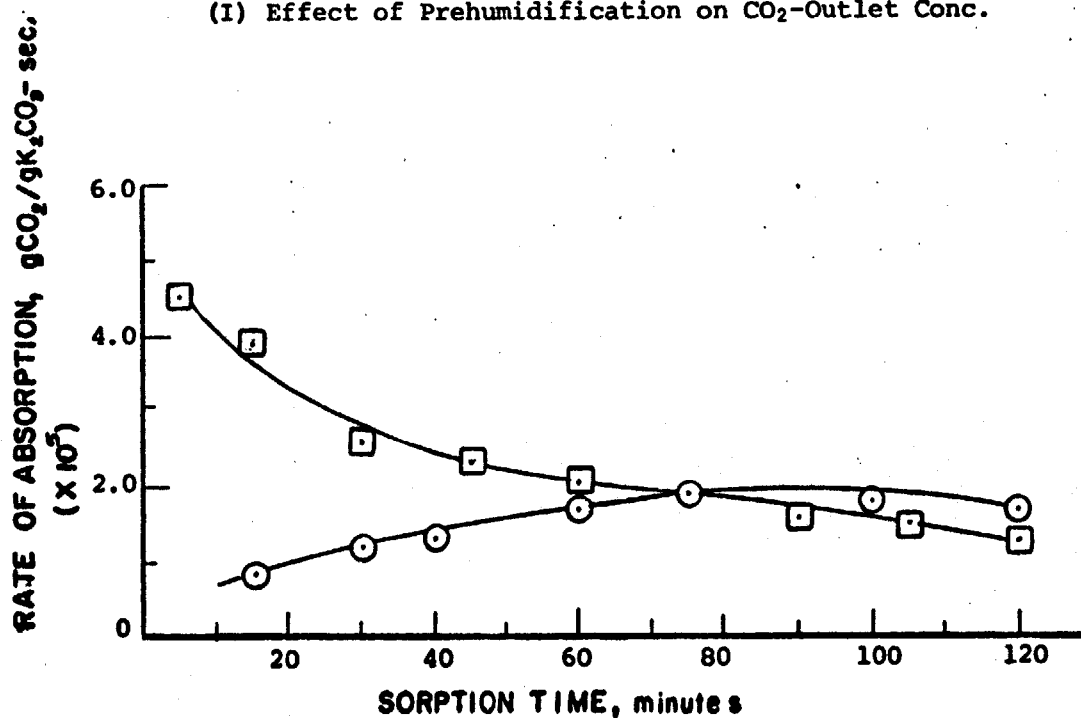
Inlet Air Flow = 21.24 lit/min.  
CO<sub>2</sub> Inlet Conc. = 7.6 mmHg  
Inlet Air Temp. = 25°C  
Cooling Air Flow = 85 lit/min.  
Absorption Time = 3.0 hours

| Regeneration Type | Sorbent Bed Temp., °C | Total Operating Pressure, mmHg | Time Required For Complete Regeneration |
|-------------------|-----------------------|--------------------------------|---|
| Thermal           | 150                   | 760                            | 2.1                                     |
| Thermal           | 120                   | 760                            | 4.0                                     |
| Thermal & Vacuum  | 120                   | 50                             | 2.2                                     |
| Thermal           | 110                   | 760                            | >4.0                                    |
| Thermal & Vacuum  | 110                   | 25                             | 2.2                                     |

| Run No. | L/D Ratio | Sorbent air Flow, lpm | CO <sub>2</sub> -in mmHg | Prehumidification        | Max. Temp, °C | max. temp, reached min. |
|---------|-----------|-----------------------|--------------------------|--------------------------|---------------|-------------------------|
| ○ 101   | 3.01      | 61                    | 7.6                      | No                       | 48            | 15                      |
| □ 105   | 3.01      | 61                    | 7.6                      | Yes, 45 minutes each end | 42            | 30                      |



(I) Effect of Prehumidification on CO<sub>2</sub>-Outlet Conc.



(II) Effect of Prehumidification on Rate of Absorption

Figure 14-b, Effect of Prehumidification on Sorber Performance



Run 101 for the same processing conditions. The maximum temperature rise in Run 105 is also 6°C lower than that of Run 101. Thus, during the initial period of sorption, pre-humidification does improve the sorber performance, but eventually it comes to the same conversion level after a few hours. The phenomena may have an interesting effect on absorber with vacuum regeneration which operates alternately on absorption and regeneration for small time intervals only. The advantage of prehumidification could outweigh the logistic disadvantage of a pre-treatment in certain modes of operation of the sorber module.

## 5.0 SORBER MODULE LIFE TESTING

The optimum sorber unit was life tested by subjecting it to a repeated cycle of absorption, desorption, and cool-down. The test station facility was provided with automatic controls to shorten life testing time. The process and instrumentation diagram illustrating control units and installation of solenoid valves is presented in Figure 15. This automation permitted two cycles per day including weekends. Everyday the instruments were calibrated and every fifth cycle the sorber performance was manually monitored.

The sorber module was endurance tested for more than 160 cycles under operating conditions as shown in Table 5. The endurance performance of the test module at sorption times of 30, 60, 120, and 180 minutes is depicted by Figure 16. The module yields carbonate conversions above 50% within three hours for almost up to 100 cycles. Table 5 shows the effect of endurance on sorbent activity in terms of its decay rate. The average loss in sorbent activity ranges from 0.0046 to 0.0338 percent drop in carbonate utilization per cycle. The decay rate is lower for low times of sorption. This suggests that the sorber module would stand even much longer endurance if it were operated for low sorption times only.

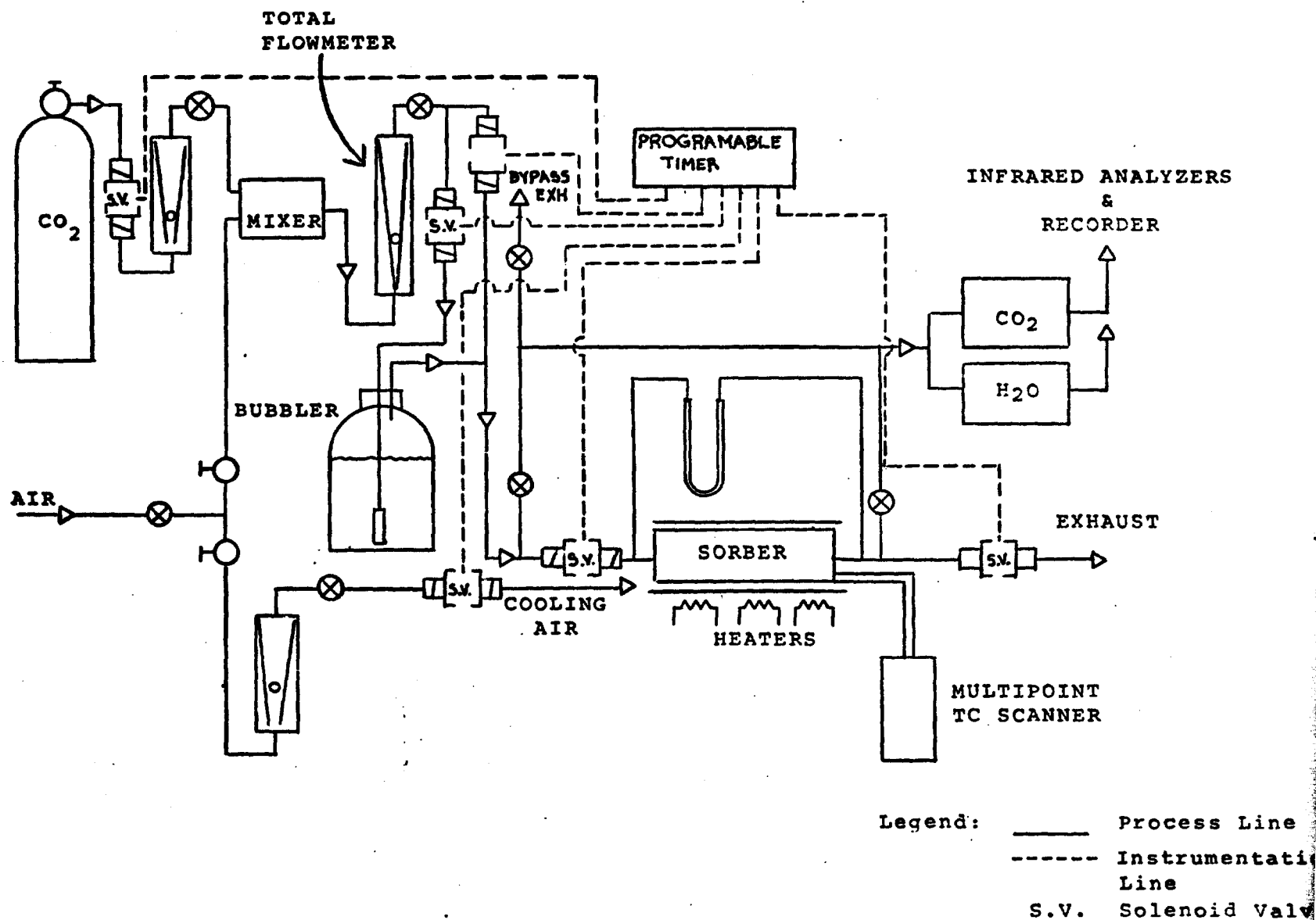


FIGURE 15 PROCESS & INSTRUMENTATION DIAGRAM FOR SORBER MODULE LIFE TESTING

INLET AIR FLOW = 21.24 Lit/min.  
CO<sub>2</sub> INLET CONC. = 7.6m.m. Hg  
TEMPERATURE = 25°C  
COOLING AIRFLOW = 84.95 Lit/min.

△ - 30 MIN.  
○ - 60 MIN.  
□ - 120 MIN.  
● - 180 MIN.

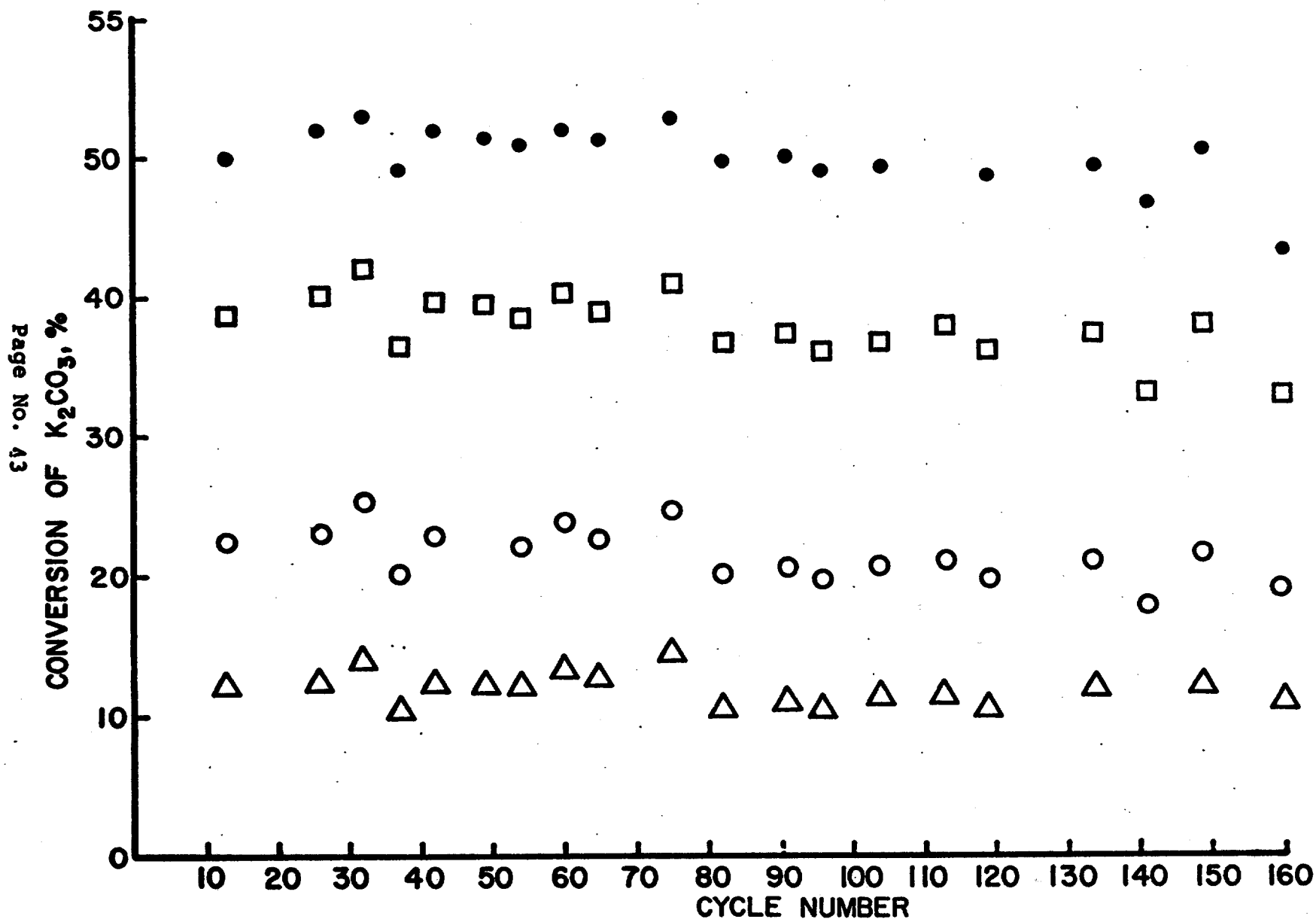


FIGURE 16, SORBER MODULE LIFE TESTING (Cooled Unit)

TABLE 5

Sorber Module Life Testing

Operating Conditions: No. canisters = 1  
 Sorption air flow = 21.24 lit/min  
 Inlet concn. of  $\text{CO}_2$  = 1.00 mole %  
 Inlet concn. of  $\text{H}_2\text{O}$  = 2.75 mole %  
 Inlet temperature =  $25 \pm 4^\circ\text{C}$   
 Wt. of carbonate = 198.2 gm

| Time<br>of<br>Sorption<br>$t$<br><br>min | Utilization<br>of $\text{K}_2\text{CO}_3$ during<br>first cycle<br>% | Decay rate of<br>Sorption activity *<br>% $\text{K}_2\text{CO}_3$ utilization drop/cycle |
|--|--|--|
| 30                                       | 12.21  | 0.005  |
| 60                                       | 23.76  | 0.028  |
| 120                                      | 41.40  | 0.054  |
| 180                                      | 52.82  | 0.034  |

\* Decay rate of sorption activity at a given sorption time,  $t$ , defined as average drop in percent carbonate utilization per cycle.

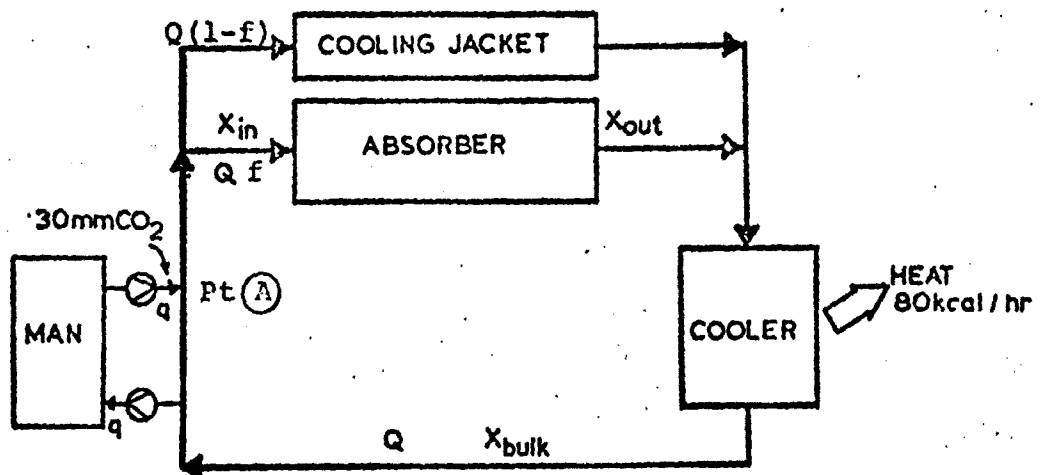
## 6.0 SYSTEM DESIGN IMPLICATIONS

Various parameters, as discussed in previous sections, effect the performance of the carbon dioxide absorber system and hence the overall PLSS. This chapter deals with the restrictions imposed by a Closed Man-Absorber System on the absorber unit and with other important parameters such as pressure drop, heat load, and cooling requirements.

### 6.1 System Performance Range

Absorber carbon dioxide removal test conditions were set to simulate realistic mission conditions. An analysis of the one-man carbon dioxide control system was made to establish the range in which a sorber could successfully operate. The system, as shown schematically in Figure 17, assumed that a portion of the recirculating suit atmosphere is available as the cooling medium which can be later mixed and cooled with the carbon dioxide free air.

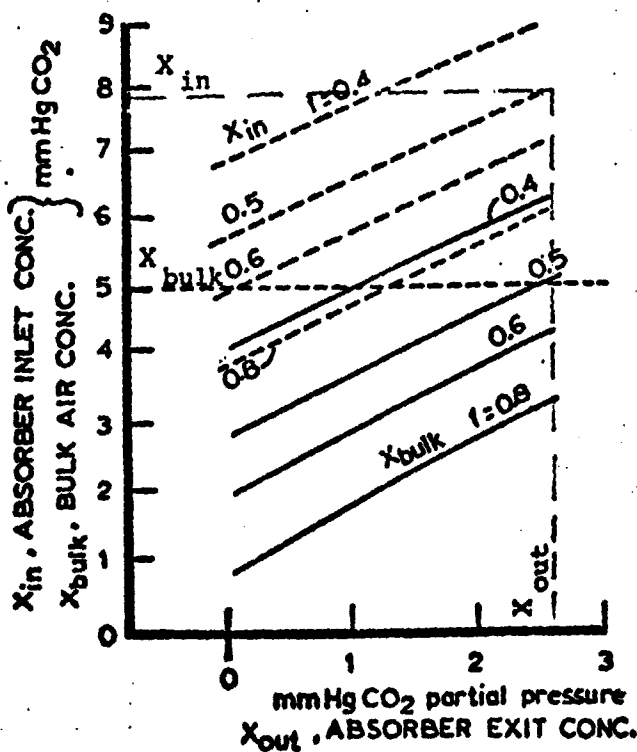
An overall mass balance on carbon dioxide entering and exiting the system and a carbon dioxide mass balance at point A yield a system of two equations and two unknowns,  $X_{in}$  and  $X_{bulk}$  (Appendix E). The incoming concentration to the sorber,  $X_{in}$  and the bulk carbon dioxide concentration,  $X_{bulk}$ , the maximum permissible concentration of  $CO_2$  in the breathing air stream, were solved as a function of  $X_{out}$ , the sorber exit concentration and the fraction  $f$ , of total flow that is split between the sorber flow and cooling flow for the sorber.



Man production: 60 liters / hr  
 $Q = 240$  liters/min  
 $q = 25$  liters/min  
 $f$ : fraction of flow

$X_{in}$ , ABSORBER INLET CONC.  
 $X_{bulk}$ , BULK AIR CONC.  
 $X_{out}$ , ABSORBER EXIT CONC.

(a) Schematic Flow Diagram



(b) Relation of Carbon Dioxide Concentrations at Various Points in a Closed Man-Absorber System.

FIGURE 17 System Performance Limits on Sorber

The input load from the man was taken at the rate of 60 liters CO<sub>2</sub> per hour. NASA system specifications of  $X_{\text{bulk}}$  were taken as 5 mm Hg partial pressure, with  $Q$  being 240 liters/per minute.

The expected range of inlet and outlet carbon dioxide concentrations, the flow rate through the absorber, and the maintenance of the 5mmHg or below partial pressure of carbon dioxide in the bulk suit atmosphere ( $X_{\text{bulk}}$ ) are related and shown in Figure 17. All the points below the bulk limit,  $X_{\text{bulk}}$ , indicate the sorber operating range for the system in terms of  $X_{\text{in}}$  and  $X_{\text{out}}$ , the incoming and exit sorber concentrations, and  $f$ , the fractional flow through the sorber.

Inlet test conditions for the absorber test units were thus taken as 7.6mmHg partial pressure carbon dioxide. As seen in Figure 17, the outlet carbon dioxide concentration can rise from zero to 2.6mmHg and still maintain the 5mmHg carbon dioxide limit in the bulk recirculating atmosphere. This 2.6mmHg limit is used as a standard of comparison of absorber performance.

Run 310 in Figure 7 and Runs 1 & 407 in Table 4 show an outlet concentration below 2.6mmHg for three hours sorption with 7.6 mmHg inlet stream. The performance of these runs is quite close to the system specification for the CO<sub>2</sub> outlet concentration.



## 6.2 Cooling Requirements

Absorption of carbon dioxide by potassium carbonate in the presence of moisture is exothermic in nature. As shown in Appendix: B, theoretical heat of carbon dioxide absorption as a function of temperature can be computed from equilibrium thermodynamics. Another simultaneous reaction taking place along with CO<sub>2</sub> absorption is absorption of free water to form hydrate, which is also exothermic. Heat of hydrate formation is -11.1 KCal/g. mole.

Computation of the combined theoretical heat load of these reactions is given in Appendix: C. As shown in Table 8, the cooling load required to maintain isothermal operation depends upon CO<sub>2</sub> removal load and extent of free water absorption to form hydrate. Table 6 gives experimentally determined heat load for these two reactions at various operating conditions. Measured heat load per gram of CO<sub>2</sub> removed varies depending upon humidity, activity of sorbent bed, and radiation and convection heat losses from the canisters.

Measurements of the inlet and outlet process air and cooling air stream temperatures, and amount of water removed confirm that ninety percent of the theoretical heat is accounted for. The ten percent difference may be attributed to the losses to the surrounding atmosphere. An overall sorber material specific heat estimate of 0.2 cal per gram-°C was assumed.

TABLE 6

Heat Load at Various Operating Conditions

| Run No. | Total Sorption Time Hour | SORPTION AIR |                |        |                  |                  |   | COOLING AIR  |                |        | ENTHALPY CHANGE KCAL/HOUR |             | CO <sub>2</sub> Removed gms/hr. | Total Heat Load* KCal/hr |
|---------|--------------------------|--------------|----------------|--------|------------------|------------------|---|--------------|----------------|--------|---------------------------|-------------|---------------------------------|--------------------------|
|         |                          | Flow Lit/min | Avg. Temp., °C |        | Conc. at Inlet % |                  | Total Prehumidification Time**, minutes | Flow Lit/min | Avg. Temp., °C |        | Sorpton Air               | Cooling Air |                                 |                          |
|         |                          |              | Inlet          | Outlet | CO <sub>2</sub>  | H <sub>2</sub> O |   |              | Inlet          | Outlet |                           |             |                                 |                          |
| 103     | 3.0                      | 60.0         | 20.8           | 33.6   | 1.0              | 2.3              | 40                                      | 56.6         | 20.8           | 25.1   | 13.28                     | 4.21        | 23.77                           | 17.49                    |
| 104     | 2.0                      | 30.0         | 21.2           | 34.6   | 1.8              | 2.2              | 40                                      | 56.6         | 21.2           | 26.1   | 6.95                      | 4.80        | 10.09                           | 11.75                    |
| 301     | 2.7                      | 60.0         | 18.9           | 28.1   | 1.0              | 2.3              | 40                                      | 64.6         | 18.9           | 22.4   | 9.55                      | 3.91        | 21.07                           | 13.46                    |
| 303     | 3.0                      | 30.0         | 18.0           | 26.5   | 1.0              | 2.1              | 50                                      | 64.6         | 18.0           | 21.4   | 4.41                      | 3.80        | 17.03                           | 8.21                     |
| 309     | 3.0                      | 14.2         | 17.7           | 23.1   | 1.0              | 2.1              | 40                                      | 85.0         | 17.7           | 19.5   | 1.33                      | 2.65        | 10.76                           | 3.98                     |

\* Due to the absorption of CO<sub>2</sub> and the hydrate formation

\*\* Sufficient cooling was done after prehumidification

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### 6.3 Pressure Drop

Pressure drop in the process stream across the sorber module depends upon the configuration of the canisters. The pressure drop thru the 300 series canisters was measured to be 20 cm of water at 59.5 liters per minute (lpm) air flow, and the single canister measured about 13 cm of water. For 400 series and cycle testing, the sorber module gave a pressure drop of 8.9 cm of water at 28.3 lpm air flow and 24.6 cm of water at 59.6 lpm. Pressure drop results for a three canister parallel configuration are tabulated in Table 7.

In general, parallel canister configuration gives less pressure drop than the series configuration. This point should be considered in the final design of the sorber unit because total power requirements for the process stream depends upon the pressure drop.

### 6.4 Performance Projections

The present study resolved relative merits of various parameters and identified most critical ones influencing the final size of the absorber. Radial heat transfer and vacuum regeneration rank among the top of these. Size estimation has been discussed in view of these two parameters in the succeeding paragraphs.

Using performance data obtained under non-isothermal conditions with a two canister in series sorber unit, the volume of an 8 hour mission unit would be 179 liters (6.3 cu.ft.). As discussed in Section 7-1, cooling system improvements have not

TABLE 7

## Pressure Drop for 3 - Parallel Canister Configuration

Operating Conditions: Inlet temperature = 25°C  
 Inlet CO<sub>2</sub> conc. = 1.0 mole %  
 Inlet H<sub>2</sub>O conc. = 2.75 mole %  
 Inlet air pressure = 19.7 psia

| Canister<br>No. | Pressure drop in inches of water   |       |       |
|-----------------|------------------------------------|-------|-------|
|                 | Inlet air flow rate, liters/minute |       |       |
|                 | 14.16                              | 21.24 | 28.32 |
| 1               | 0.25                               | 0.375 | 0.625 |
| 2               | 0.25                               | 0.312 | 0.500 |
| 3               | 0.25                               | 0.375 | 0.625 |
| Total System    | 0.375                              | 0.625 | 1.125 |

been exhausted and nearly isothermal operation is theoretically and practically possible. On this basis, the estimated size and weight of a one-man, eight hour unit is estimated to be 8.3 kg (without separator material) and 78 liters volume (2.8 cu.ft.). The basis of the scale-up estimate considered 75 percent carbonate conversion which was typically achieved in the isothermal single sheet sorbent channel apparatus. The carbon dioxide input duty was taken as that corresponding to an average metabolic rate of 302 kcal per hour producing 60 liters of carbon dioxide per hour.

#### Effect of Simultaneous Absorption and Regeneration on Size of the Absorber:

With vacuum regeneration, half of the sorber module can operate on absorption and the other half on regeneration. A conservative estimate for eight hour mission with two hours of alternate absorption or regeneration (cycle time) time would reduce the size of the absorber to 39 liters volume. For 15 minutes of cycle time, the size of the absorber unit with simultaneous absorption and regeneration will reduce to 20 liters (0.7 cu.ft.) based on the projected performance from the present study. The weight of this unit is estimated to be 6.2 kg (13.7 lbs.) including separator material, cooling jacket and fittings. With the improved heat transfer, this unit size will further reduce to about 12-15 liters (0.4-0.5 cu.ft.) and 4-5 kg (9-11 lbs.) weight.

A sorber module operating on simultaneous absorption and regeneration in alternate sorption layer will have much better

capacity than all other configurations. Projections on this type of unit based on results of absorption in Channel type geometry show a final volume of the absorber between 8 to 12 liters based on one half hour of cycle time.

## 7.0 ADVANCED CONCEPTS

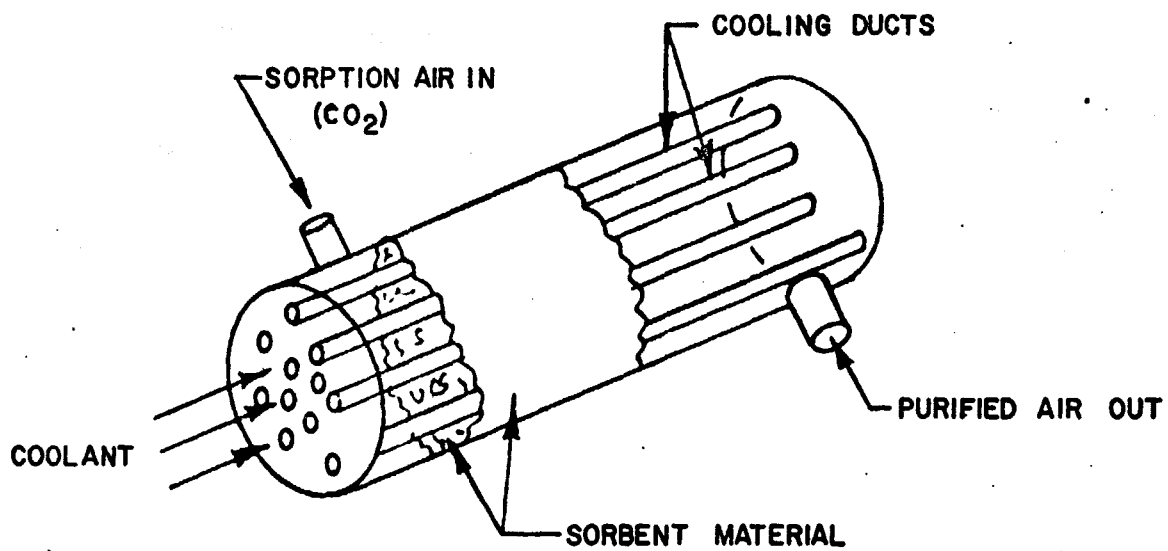
The environmental carbon dioxide removal system with an additional advantage of humidity removal has good performance merits in terms of longer cycle life and maintaining low outlet concentrations. However, incorporation of various concepts resulting from the present study would make it a most competent and acceptable unit for PLSS applications. The prime factors are design and development of schemes to improve radial heat transfer for isothermal operation and vacuum regeneration.

### 7.1 Schemes for the Improvement of the Radial Heat Transfer

An improved sorbent cooling system to maintain isothermal sorbent conditions near 20°C would, as mentioned and shown in previous reports, increase the conversion of potassium carbonate while maintaining low levels of CO<sub>2</sub> outlet concentration.

The present study employed an air cooled system only, which has low heat transfer coefficients as compared to a liquid cooled system. Selection of a proper coolant, probably water, can aid heat transfer.

Radial conduction can be enhanced by a specially designed flow profile with a shortened path of heat transfer. A simple improvement in design can be a canister with two annular and a central cooling jacket as shown in Figure 4-b. Alternately, multiple array of small diameter, thin walled cooling tubes across the sorber cross-section with the possible use of liquid coolant is a better temperature control method to investigate. Figure 10 elucidates this system in which the radial distance



**FIGURE 18**  
**CANISTER WITH MULTIPLE ARRAY COOLING TUBES**



for heat transfer is reduced. The only disadvantage in multiple array cooling tubes system is packing density of sorbent material. Multiple tubes would reduce effective space for sorbent packing. It appears that gain obtained by better heat transfer may be counterbalanced by an increase in unit size.

A system having better heat transfer at a small cost of packing density loss is presented in Figure 19. The concept in this configuration is similar to the equilibrium cascade operation. The canister is divided into a number of subsections by baffles. Sorption air passes through the first section. Heat of absorption released in the small section is removed by an axial and an annular cooling jacket. Air at the end of the first section is mixed and redistributed in channels of the next section. Direct contact with cooling jackets would yield better cooling of mixed air between two sections. Air flow between two sections is directed radially either inward or outward giving almost isothermal operation and reduced radial temperature gradient. Higher conversion levels seem attainable by this configuration with a cross flow liquid cooling.

A sorber unit having this configuration can be fabricated with only minor changes in the manufacturing technique developed at ERC.

## 7.2 Vacuum Regeneration Schemes

Reactivation of the sorbent material may be possible at near ambient temperatures if desorption is carried out under high vacuum. Due to very low total pressure, desorption rates can be expected to be diffusion independent. Since this would result in a decrease

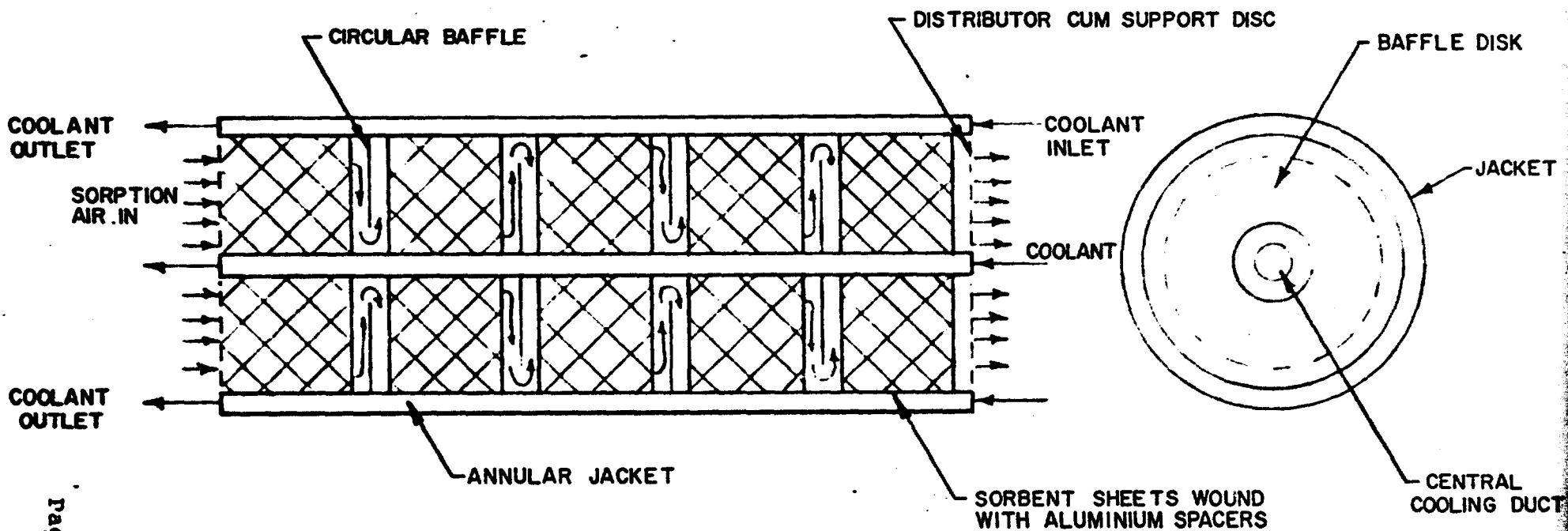


FIGURE 19  
SCHEMATIC CONFIGURATION FOR IMPROVED RADIAL HEAT CONDUCTION

of regeneration time, the sorber module can be operated with two units, either of them absorbing or regenerating. Heat of desorption can be supplied by a low duty heating coil wound spirally with the sorbent sheet. With two hours of regeneration time, the size of the present absorber would be reduced to one half of the eight hour mission size unit. This can even be further reduced if simultaneous absorbing and regenerating units are employed along with improved radial heat transfer.

The most compact unit with minimum energy requirements is possible if the sorber module is designed to operate on the principle of simultaneous absorption and desorption in alternate sorbent layers. Two types of sorbent packing geometry are possible: cylindrical and cubical. As shown in Figure 20, the sorbent sheets are packed in the form of concentric cylinders with aluminum or S.S. spacers to have proper channels for gas flow. The baffle arrangement is such that sorption air passes through every alternate channel only. The other set of alternate channels can be connected to the vacuum system for regeneration. Heat generated by the carbon dioxide absorption is conducted through the sorbent sheet to the other side under the vacuum, where it is utilized as heat of desorption. This maintains the absorption side under isothermal conditions while providing endothermic heat of desorption.

Cubical geometry, as shown in Figure 21, is simpler than cylindrical configuration. Rolling of concentric cylindrical sheets with a good seal under ultra high vacuum requires a very careful and accurate fabrication technique. While in cubical

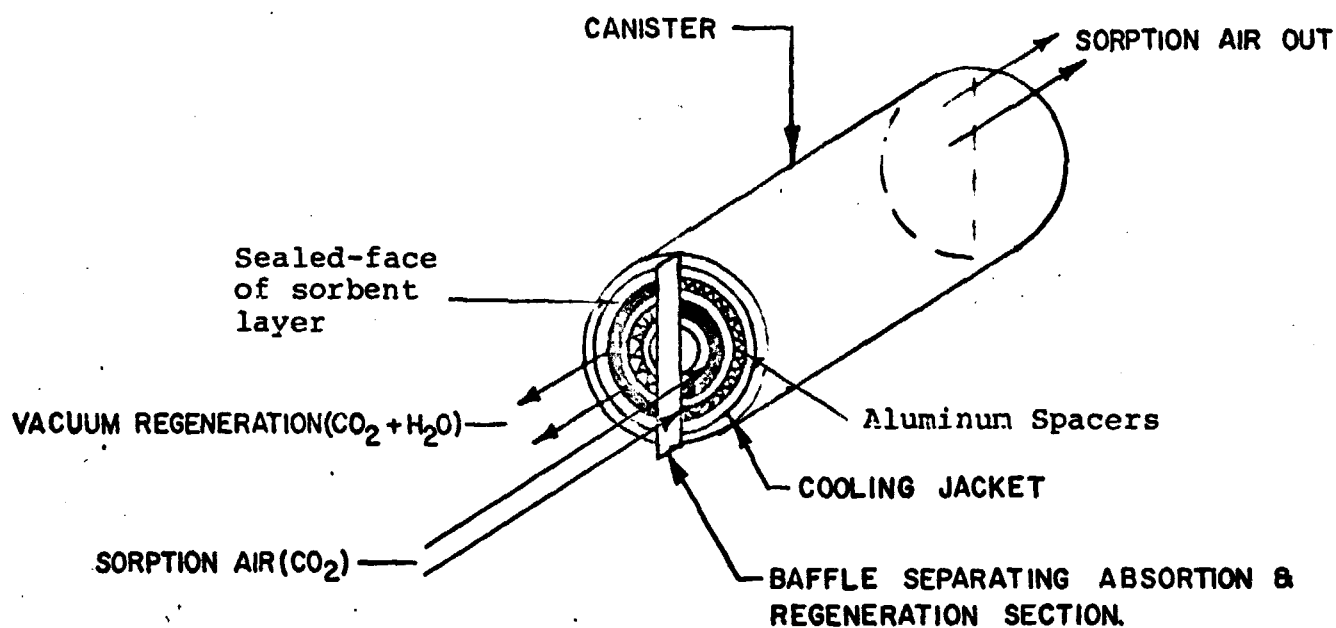
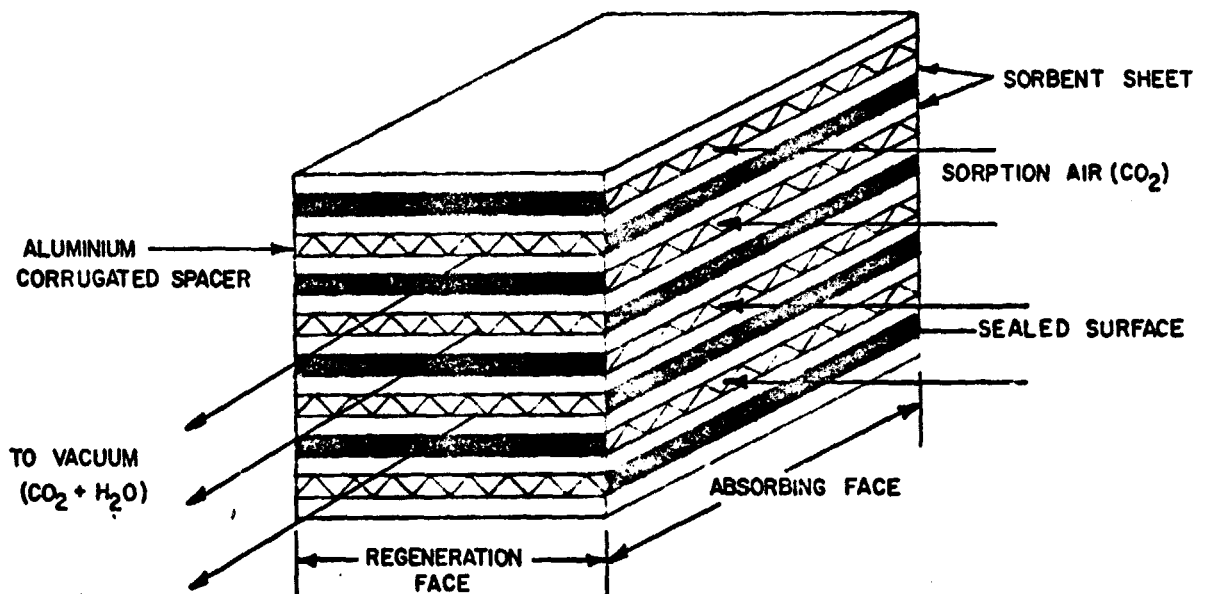


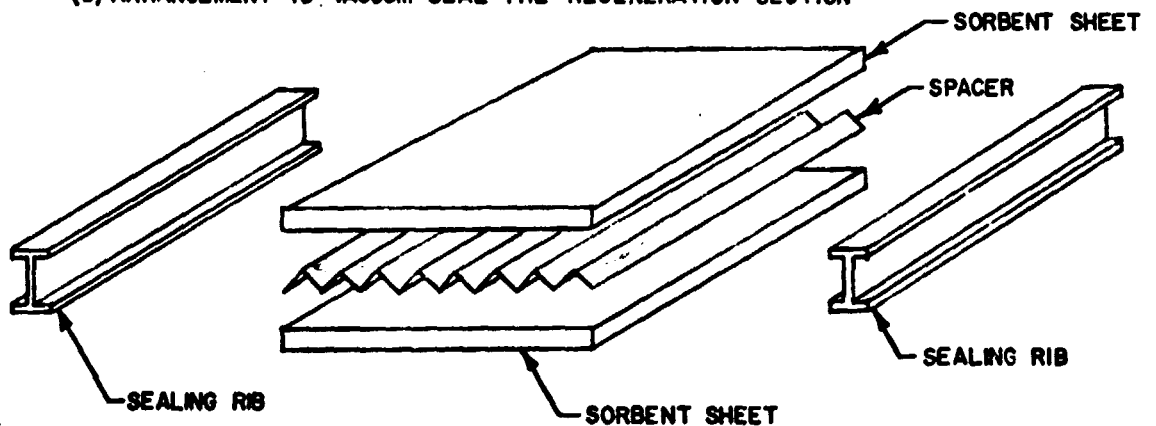
FIGURE 20

SIMULTANEOUS ABSORPTION AND REGENERATION IN ALTERNATE SORBENT LAYERS(CYLINDRICAL GEOMETRY).

(a) FLOW CONFIGURATION FOR SIMULTANEOUS ABSORPTION AND REGENERATION.



(b) ARRANGEMENT TO VACUUM SEAL THE REGENERATION SECTION



**FIGURE 21**  
SIMULTANEOUS ASORPTION AND REGENERATION IN ALTERNATE SORBENT LAYERS (CUBICAL GEOMETRY).

geometry, the plain sheets are easier to stack up with accurate channel spacing and proper vacuum seals. Cubical arrangement is similar to a battery developed at ERC with cross flow cooling. Fabrication technique for this battery can be extended to the design of the cubical unit without serious problems. Sealing arrangement for this is shown in Figure 21. The cooling jacket is optional in these units. It may be required when the outermost layer is in the absorption mode.

Since sorbent material has low thermal conductivity, analysis was made to check for high temperature gradients across the sorbent material. Analysis assumed a sorbent coating on both sides of a thin S.S. plate for good strength against vacuum. As shown in Appendix D, the temperature gradients will be very small - of the order of few degrees. Appendix C shows how system temperature would rise if it operates adiabatically. In this configuration, heat will be conducted to the next surface giving two-fold advantage - cooling for sorption side and heating for desorption.

Absorption/Desorption with cubical configuration is quite similar to an earlier study with one channel only. The high performance level obtained under channel study makes this unit a candidate system for further investigation.

To summarize, the simultaneous absorption and regeneration in alternate sorbent layers packed in a cubical system has the following advantages:

- a) Minimum thermal swings of the bed during absorption and regeneration.
- b) Most economic system with good energy conservation.
- c) Radial conduction heat transfer is no longer a problem.

- d) Elimination of active heating or cooling. Outlet concentration can vary up to 5 mmHg instead of 2.6 mm Hg with air cooling.
- e) High conversion levels can be attained while maintaining good cycle life of the unit.
- f) High probability to have most compact size.

## 8.0 CONCLUSIONS AND RECOMMENDATIONS

The potassium carbonate-bicarbonate system was tested in the prototype absorber unit for the PLSS. With proper temperature control, the solid potassium carbonate absorbers offer the advantage of a safe, nontoxic regenerable system. Reusable absorber units would save a large portion of the lift weight of non-regenerable units. Although a thermal regeneration system on the base station presents an additional power and weight penalty, the low regeneration temperature of 150°C and the partial reduction of suit humidity are advantageous system features. The limiting parameter in the present system is the volume of the absorber unit. The annular-cooled prototype absorber unit would scale up to the maximum 8 hr., one-man duty unit weighing 15.8 kg (without separator material). The unit with thermal regeneration and improved heat transfer design to achieve high carbonate utilization (carbonate conversions up to 75-80% are conceivable) will be of acceptable size for a 4-hour mission. However, this system appears to be very attractive if it operates on the principle of simultaneous absorption and regeneration. Preliminary results of combined vacuum and thermal regeneration showed that the size of the absorber may be reduced to about 1/3 to 1/2 cu.ft. for the eight-hour mission. This system will absorb CO<sub>2</sub> and water vapor from the suit-air and desorb the CO<sub>2</sub> and water vapor when exposed to a space vacuum. Continuous operation can be achieved by utilizing two beds which are alternately cycled between absorption and desorption.



In order to achieve high reaction rates and conversion levels, the various concepts for the improved radial heat transfer with possible use of liquid coolants should be further explored. One of the probable coolant systems may be the same fluid as that used in space-suit for the temperature control. The excess heat energy contained in the suit-coolant may be used to provide heat for the thermal regeneration. This will have an additional advantage of reducing the heat load on the suit-coolant loop. Vacuum regeneration technique under ultra high vacuum should be investigated to a greater depth. Incorporation of vacuum regeneration will not only reduce thermal energy requirements for regeneration but also reduce cooling requirements considerably. Combination of simultaneous vacuum and thermal regeneration may also be a probable candidate for the final absorber design. This system will be self-sufficient for the energy requirement except for the irreversibility and heat losses.

APPENDIX A

PORE STRUCTURE OF THE SORBENT SHEET MATERIAL



FIGURE 22a

S.E.M. PICTURES OF A SORBENT SHEET HAVING OPTIMUM COMPOSITION

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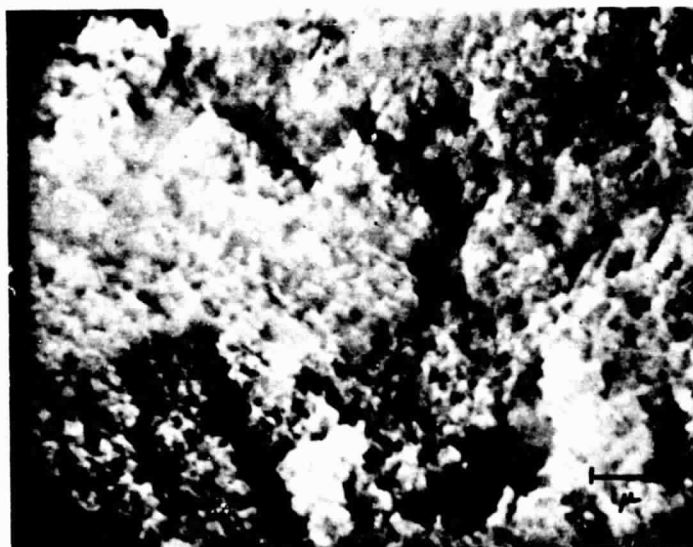


FIGURE 22b

S.E.M. PICTURES OF A SORBENT SHEET HAVING OPTIMUM COMPOSITION

Sample: A

Composition:

$K_2CO_3$ : 44.0 w %

Silica Gel: 53.0 w %

Teflon: 3.0 w %

Method Used: Mercury Intrusion

Porosity: 93.6 %

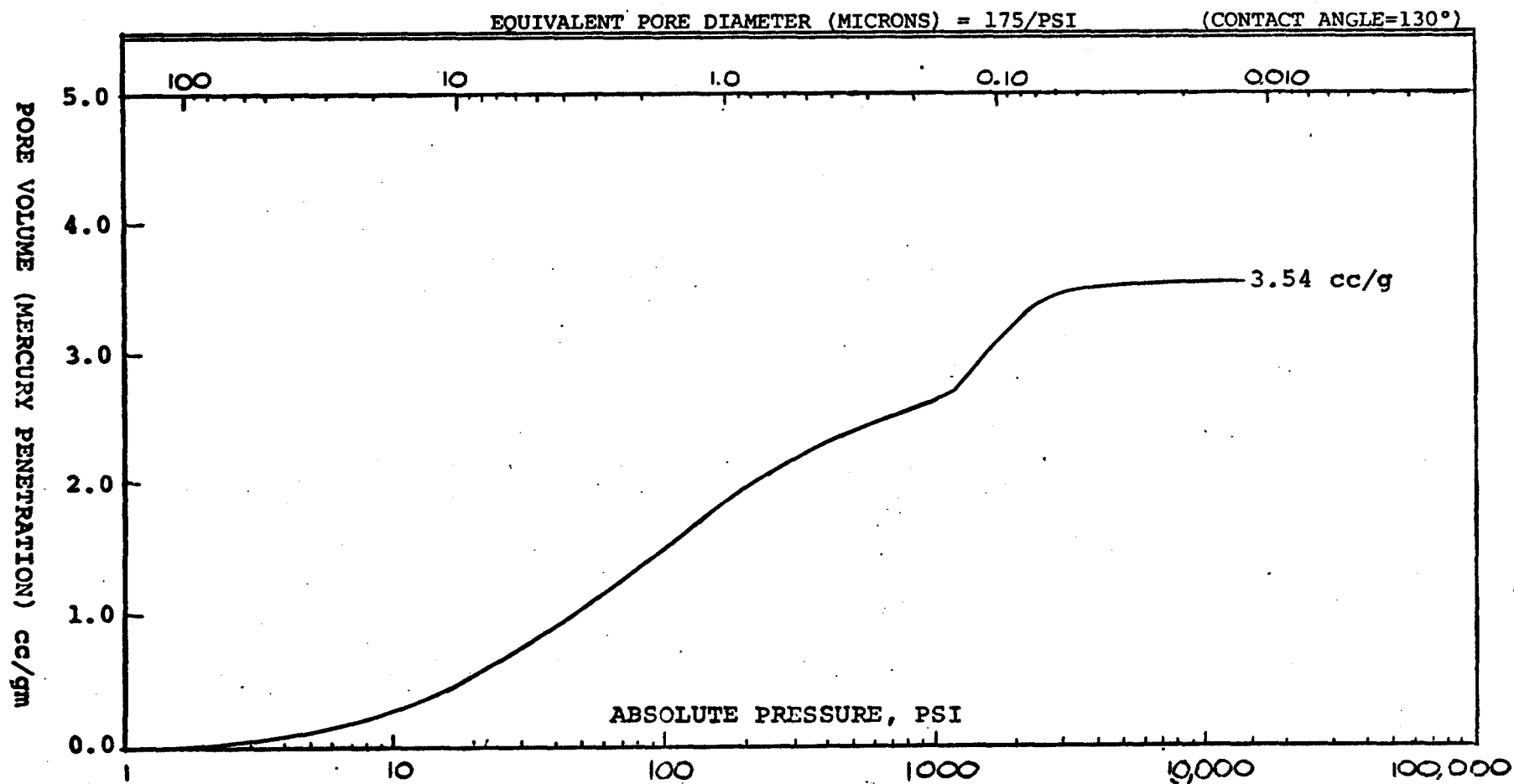


FIGURE 23 a PORE SIZE DISTRIBUTION OF THE SORBENT SHEET

Sample: B

Composition:             $K_2CO_3$ : 43.0 w %  
                         Silica Gel: 54.0 w %  
                         Teflon: 3.0 w %  
Method Used: Mercury  
                         Intrusion  
Porosity: 89.8 %

EQUIVALENT PORE DIAMETER (MICRONS) = 175/PSI (CONTACT ANGLE=130°)

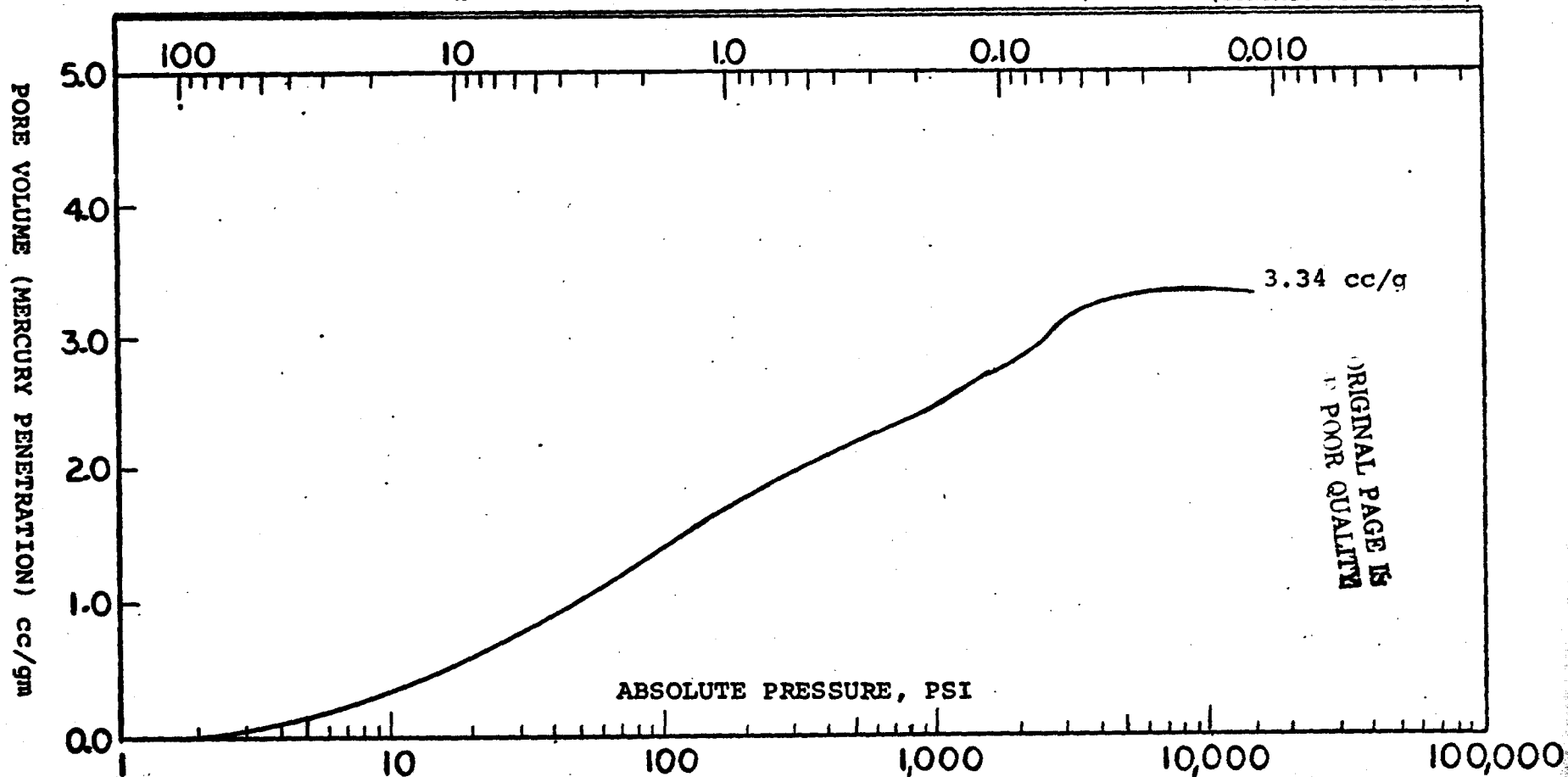


FIGURE 23 b PORE SIZE DISTRIBUTION OF THE SORBENT SHEET

## APPENDIX: B

Heat of Reaction

Heat of absorption of carbon dioxide to form potassium bicarbonate was estimated from equilibrium thermodynamics (5). The equilibrium constant  $K_p$ , defined in terms of partial pressures, for the reaction



is given by the following expression (1):

$$\log_{10} K_p = \frac{6593}{T} - 4.26 \log_{10} T - 0.32 \times 10^{-3} T - 5.551 \quad \text{---(1)}$$

$$\text{where: } K_p = \frac{1}{(P_{CO_2}) (P_{H_2O})} = \frac{1}{(P_{CO_2})^2}$$

$$\text{Total Pressure, } P_T = P_{CO_2} + P_{H_2O} = 2 P_{CO_2} \text{ (atm.)}$$

(Note: The equilibrium constants  $K$  and  $K_p$  are equal for ideal gases.)

Let,

$\Delta H^\circ$  = standard state heat of reaction at any temperature,  $T$ ,  $^\circ K$ .

$\Delta F^\circ$  = standard state free energy change at temperature,  $T$ ,  $^\circ K$ .

Basic relationship for free energy variation of a single component is given by:

$$dF = Vdp - SdT \quad \text{---(2)}$$

For a constant pressure system, this takes the form

$$dF = -SdT$$

or

$$\left(\frac{\partial F}{\partial T}\right)_p = -S \quad \text{---(3)}$$

For a chemical reaction between the standard states of the reactants and products equation -(3) at equilibrium becomes

$$\frac{d(\Delta F^\circ)}{dT} = -\Delta S^\circ \quad \text{---(4)}$$

Standard free energy change is related to equilibrium constant by

$$\Delta F^\circ = -RT \ln K \quad \text{---(5)}$$

also, for constant temperature reaction process

$$F = H - TS$$

$$\Delta F^\circ = \Delta H^\circ - T \Delta S^\circ \quad \text{---(6)}$$

Equation (4) and (6) yields

$$\frac{d(\Delta F^\circ)}{dT} - \frac{\Delta F^\circ}{T} = -\frac{\Delta H^\circ}{T} \quad \text{---(7)}$$

Integration of Equation (7) results into

$$\frac{\Delta F^\circ}{T} = - \int \frac{\Delta H^\circ}{T^2} dT \quad \text{---(8)}$$

Combining equation (5) and (8)

$$R \ln K = \int \frac{\Delta H^\circ}{T^2} dT$$

or

$$\frac{d (\ln K)}{dT} = \frac{\Delta H^\circ}{RT^2} \quad \text{---(9)}$$

or

$$\frac{d (\ln K)}{d (1/T)} = - \frac{\Delta H^\circ}{R} \quad \text{---(10)}$$

For ideal gas behavior, we have

$$K = K_p$$

and hence Equations (1) and (10) become

$$\frac{(-\Delta H^\circ)}{R} = 15180.94 + 4.26 T + 0.7368 \times 10^3 T^2 \quad \text{---(11)}$$

For  $R = 1.987 \text{ cal/g.mole-}^\circ\text{K}$ , temperature dependence of the heat of reaction is expressed by

$$(-\Delta H^\circ) = 30164.535 + 8.4646 T + 1.4641 \times 10^3 T^2 \quad \text{---(12)}$$

Figure 24 represents this relationship graphically.



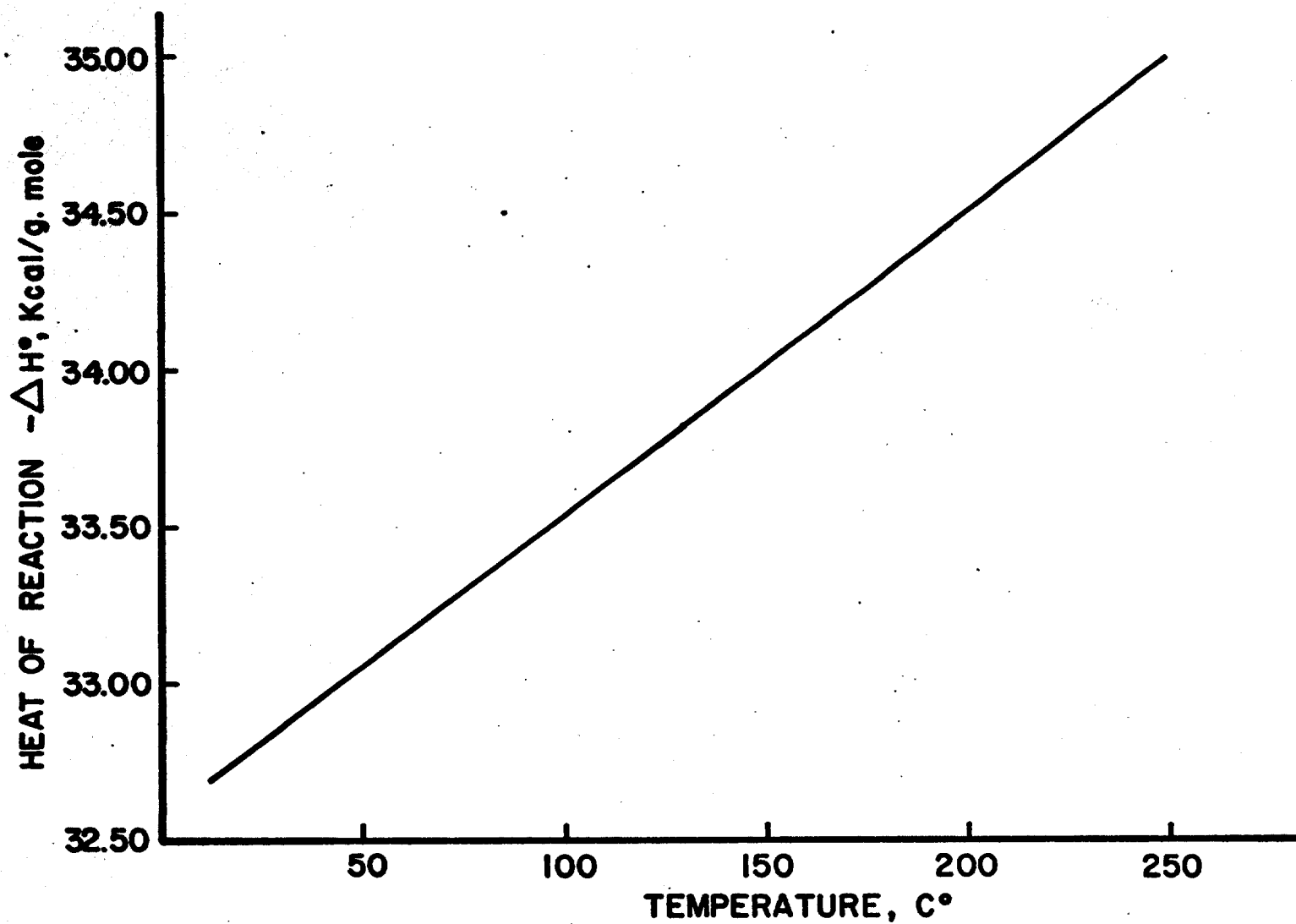


FIGURE 24  
HEAT OF REACTION OF POTASSIUM CARBONATE - BICARBONATE SYSTEM

## APPENDIX: C

HEAT LOAD AND ADIABATIC TEMPERATURE RISE AS A  
FUNCTION OF OPERATING CONDITIONS

Total theoretical heat load from exothermic absorption of carbon dioxide and hydrate formation was computed by material balance of carbon dioxide and water.

Let

$\dot{m}$  = sorption air flow rate, gm.moles/min.

$C_i$  = mole fraction of  $\text{CO}_2$  at inlet.

$W_i$  = mole fraction of water at inlet

$C_f$  = mole fraction of  $\text{CO}_2$  at outlet

$W_f$  = mole fraction of water at outlet

$\Delta H_R$  = Heat of absorption of  $\text{CO}_2$ , Cal/gm.mole  
= -32,817 cal/gm.mole at 25°C (Appendix: B)

$\lambda$  = heat of hydrate formation, cal/gm mole  
= -11,100 cal/gm.mole

$C_p$  = specific heat of air at room temp., cal/gm.mole, °C  
= 6.95 cal/gm.mole, °C

$Q$  = total heat released due to  $\text{CO}_2$  absorption and hydrate formation, cal/min

$\Delta T$  = temperature rise under adiabatic conditions, °C

Now, Heat of absorption of  $\text{CO}_2$  =  $\dot{m} (C_i - C_f) \Delta H_R$

and, Heat of hydrate formation =  $\dot{m} [(W_i - W_f) - (C_i - C_f)] \lambda$

Total heat released will be,

$$Q = \dot{m} [(C_i - C_f) (\Delta H_R - \lambda) + \lambda (W_i - W_f)] \quad \text{---(1)}$$

Temperature rise of the process air (sorption air) under adiabatic conditions can be estimated based on the following assumptions:

1. All the heat released is absorbed by the process air.
2. All heat losses from the canister are neglected.
3. Temperature gradient between the process air and the sorbent bed is neglected.
4. The process air flow,  $\dot{m}$ , is constant throughout the length of the sorber.

The adiabatic temperature rise will be,

$$\Delta T = \frac{1}{C_p} [(C_i - C_f) (\Delta H_R - \lambda) + \lambda (W_i - W_f)] \quad \text{---(2)}$$

Computed values of total heat load and adiabatic temperature rise using equation (1) and (2) are presented in Table: 8.

TABLE 8

HEAT LOAD AND ADIABATIC TEMPERATURE RISE OF  
SORBER SYSTEM FOR VARIOUS OPERATING CONDITIONS

Composition of Inlet Stream: CO<sub>2</sub>: 1.0 mole %

H<sub>2</sub>O: 3.0 mole %

| Composition of Outlet Stream |                            | Heat Released<br>at 28.3 lpm<br>air flow at 25°C<br>cal/min. | Adiabatic<br>Temperature<br>Rise, $\Delta T$ ,<br>°C |
|------------------------------|----------------------------|--|--|
| CO <sub>2</sub><br>mole %    | H <sub>2</sub> O<br>mole % |  |  |
| 0.00                         | 0.0                        | 635  | 78.9   |
| 0.20                         | 0.0                        | 584  | 72.6   |
| 0.20                         | 0.5                        | 570  | 70.9   |
| 0.20                         | 1.0                        | 557  | 69.3   |
| 0.20                         | 2.0                        | 530  | 65.9   |
| 0.34*                        | 0.0                        | 549  | 68.2   |
| 0.34                         | 0.5                        | 535  | 66.5   |
| 0.34                         | 1.0                        | 521  | 64.8   |
| 0.50                         | 0.0                        | 508  | 63.2   |
| 0.50                         | 0.5                        | 496  | 61.6   |
| 0.50                         | 1.0                        | 482  | 59.9   |

\*i.e. partial pressure of carbon dioxide is 2.6 m.m.Hg

## APPENDIX L

EFFECTIVE THERMAL CONDUCTIVITY AND TEMPERATURE GRADIENT  
ACROSS SORBENT SHEETD-I Determination of Effective Thermal Conductivity of the Sorbent  
Sheet with Spacers and Air Channels

General solution for heat transfer in a solid cylindrical body is given in following dimensionless form.

$$\frac{T - T_R}{T_O - T_R} = \sum_{n=1}^{\infty} A_n e^{-(\lambda R)^2 \frac{\alpha \theta}{R^2}} \cdot J_0 \left[ (\lambda R) \frac{r}{R} \right] \quad \text{---(1)}$$

$$\lambda R = f \left( \frac{hR}{k} \right)$$

where T = Temp. at any radius r and time  $\theta$

$T_R$  = Temp. at wall

R = Radius of cylinder

$T_O$  = Initial temp.

$\alpha$  = Thermal diffusivity =  $K/\rho \cdot C_p$

$\theta$  = Time

k = Thermal conductivity

$J_1$  &  $J_0$  = Bessel function

and the constant  $A_n$  is given by

$$A_n = \frac{2 (T_O - T_R) J_1(\lambda R)}{R [J_0^2(\lambda R) + J_1^2(\lambda R)]} \quad \text{---(2)}$$

Effective thermal conductivity of the composite sorbent core was estimated using experimental data and assuming one half of

the sorbent core as equivalent to a solid cylinder having same area of cross section for gas flow.

Temperature at the center of equi-solid cylinder,  $T = 75^{\circ}\text{F}$

Temperature at the inlet,  $T_0 = 66^{\circ}\text{F}$

Temperature at the wall,  $(r=R), T_R = 68^{\circ}\text{F}$

Diameter of the equivalent solid cylinder = 0.23 ft

Residence time,  $\theta = 2.0$  second

Density of the sorbent core, = 15.6 lb/ft<sup>3</sup>

Specific heat of the sorbent core (assumed) = 0.2 Btu/lb,  $^{\circ}\text{F}$

Equations (1) and (2) were solved for effective thermal diffusivity which gave an approximate value of effective thermal conductivity:

$$K_{\text{eff}} = 1.19 \text{ Btu/sq.ft.hr.} (^{\circ}\text{F/ft})$$

which is almost in the range of building material.

#### D-II Temperature Gradient Across the Sorbent Sheet

For a system employing simultaneous regeneration and absorption, the temperature gradient can be estimated as follows:

Assume a configuration having 100 mils thick S.S. sheet with 40 mils coating of potassium carbonate on either side. The thermal conductivities of S.S. and sorbent sheets are 7.8 and 1.19 Btu/ft.hr. $^{\circ}\text{F}$ , respectively.

$$\frac{K}{l} = \frac{1}{R_{\text{s.s.}} + R_{\text{sorbent, total}}}$$

Where,

$l$  = total thickness of sorbent i.e.

=  $t_{\text{s.s.}} + 2t_{\text{sorbent}}$

$R_{\text{s.s.}}$  = thermal resistance of s.s. sheet

$$\therefore \frac{K}{l} = \frac{1}{\frac{t_{s.s.}}{K_{s.s.}} + \frac{2t_{sorbent}}{K_{sorbent}}}$$

$$= 151.5$$

Total heat flux obtained in all the sorption runs (Table 6) range from 3 to 18 Kcal/hr (12-71 Btu/hr) so taking twice the maximum of measured heat flux,

$$\text{i.e. } q = 142 \text{ Btu/hr}$$

Hence, the temperature gradient in the sorbent sheet will be

$$\Delta t = \frac{q}{k/l}$$

$$\doteq 1^{\circ}\text{F}$$

## APPENDIX E

## MASS BALANCE EQUATIONS

The following demonstrates the relationship between CO<sub>2</sub> concentration limits and the absorber performance parameters by material balance. The schematic flow diagram used to develop these equations is shown in Figure 17a.

Let,

$X_{\text{bulk}}$  = mole fraction of CO<sub>2</sub> in the air stream for respiration,

$X_{\text{exhaust}}$  = mole fraction of CO<sub>2</sub> in exhaust air stream (from astronaut respiration),

= 0.04 (30 mmHg)

$X_{\text{in}}$  = mole fraction of CO<sub>2</sub> in the inlet stream to the sorber module

$X_{\text{out}}$  = mole fraction of CO<sub>2</sub> in the outlet stream from the sorber module

$Q$  = Total flow rate of bulk respiratory air, liters/min.  
= 240 liters/min.

$q$  = flow rate of air used for breathing, liters/min.  
= 25 liters/min.

$f$  = fraction of bulk air flow passed through the CO<sub>2</sub> absorber

$1-f$  = fraction of bulk air flow passed through the cooling jacket

Man Production rate of CO<sub>2</sub> = 1.0 liter/min

A mass balance at point A (Figure 17a) yields the following equation

Incoming CO<sub>2</sub> = Outgoing CO<sub>2</sub>

or,

$$(X_{\text{exhaust}}) q + (X_{\text{bulk}}) (Q-q) = Q (X_{\text{in}}) \quad \dots (1)$$



An overall mass balance of CO<sub>2</sub> gives the following equation

Amt. of CO<sub>2</sub> produced by astronaut = Amt. of CO<sub>2</sub> removed by  
the absorber

or,

$$q (X_{\text{exhaust}} - X_{\text{in}}) = Qf (X_{\text{in}} - X_{\text{out}}) \quad . . . . (2)$$

Equations (1) and (2) were solved for  $X_{\text{in}}$  and  $X_{\text{bulk}}$  as  
function of  $X_{\text{out}}$  for various values of  $f$ , the fractional air  
flow used for cooling. The results are plotted in Figure 17b.

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